chapter

6 Acids and Bases

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To survive in nature using only natural substances requires a very practical form of knowledge. The Cree and other Aboriginal peoples knew the best locations to harvest and plant manomin (wild rice), and various Aboriginal peoples used mosses as diaper materials and animal organs for tanning hides. From a scientific perspective, these examples all depend in some way on the presence of acids and bases. Antacid remedies for indigestion, pH-balanced shampoos, and acetylsalicylic acid (ASA) are just a few of the many acidic or basic products found in any drugstore.

Many acids and bases are sold under common or traditional names. Concentrated hydrochloric acid is sometimes sold as muriatic acid. Sodium hydroxide, called lye as a pure solid, has a variety of brand names under which it is sold as a concentrated solution for cleaning plugged drains. Generic or "no-name" products often contain the same kind and quantity of active ingredients as brand-name products. You can save time, trouble, and money by knowing that, in some cases, the chemical names of compounds used in home products are stated on the label.

Since so many technological applications involve acids and bases, it is important to understand these substances. References in the popular media offer little insight into what these substances are or what they do. Such references often emphasize one perspective, such as environmental damage caused by acid deposition or an acid spill. This can be confusing. An amateur gardener who has just read an article attributing the destruction of conifer forests to acid deposition (**Figure 1**) may be puzzled by instructions on a package of evergreen fertilizer stating that evergreens are acid-loving plants. Understanding acids and bases gives us the background to assess the beneficial and detrimental effects of acids and bases on the environment, and to evaluate technologies that are used to combat environmental problems.

STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. What is pH? How is it determined, and how does pH relate to solutions encountered in everyday life?
2. How is scientific knowledge of acids and bases applied in industrial, environmental, and consumer contexts?
3. What is the distinction between strong and weak acids or bases?

Career Connections:
Ecologist; Medical Laboratory Technologist

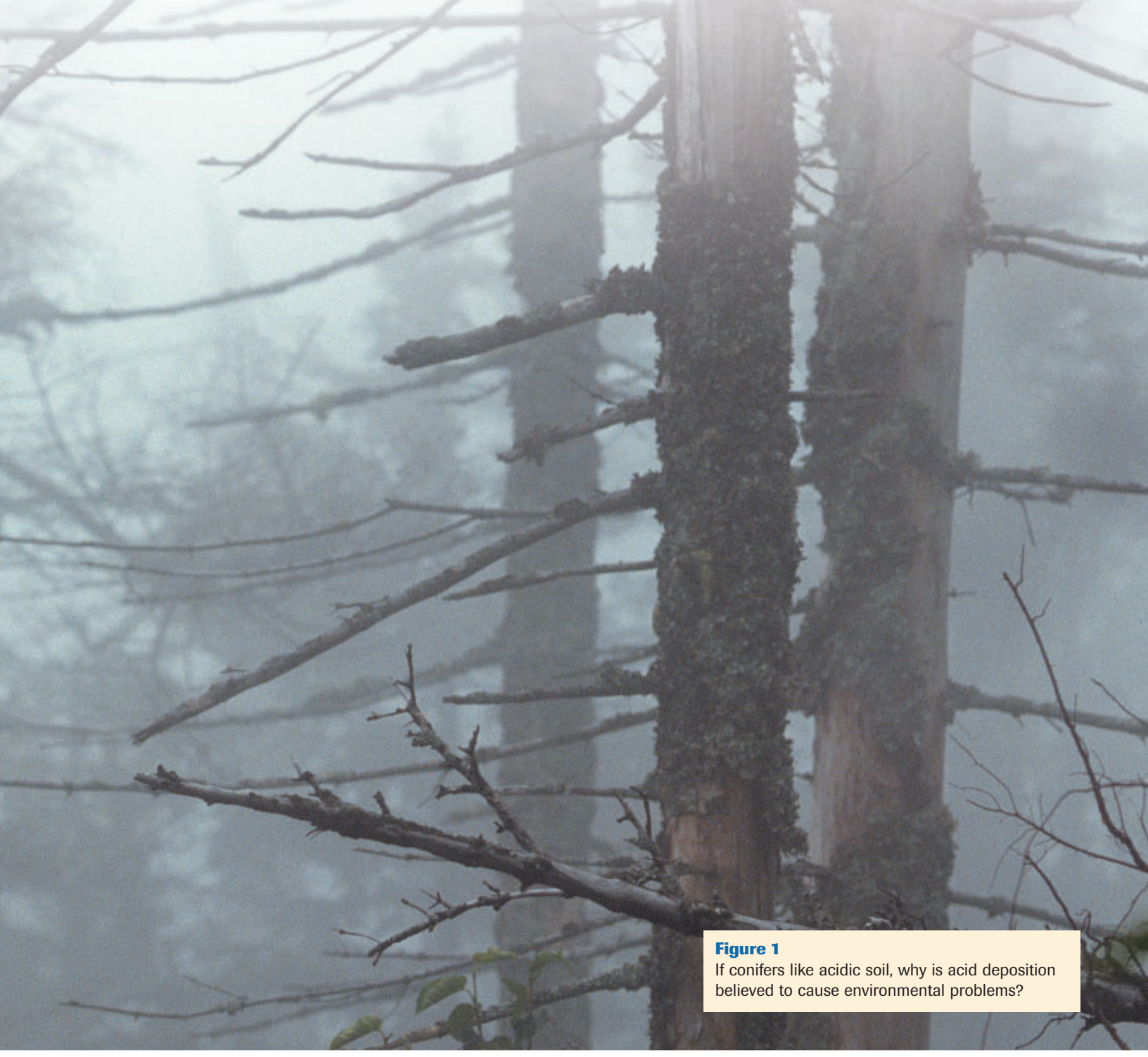

Figure 1
If conifers like acidic soil, why is acid deposition believed to cause environmental problems?

Exploration Consumer Products

Look around at home or in a store and read the labels on a variety of consumer products, such as shampoos, soaps, and other cleaners. It is not necessary to open any containers. Find one type of product that mentions pH, and investigate other brands of this product. For each brand:

(a) Record the brand name and any pH information (none, qualitative, or quantitative).

(b) What claims are made about the product's performance, and the relationship between pH and the product's performance?

(c) Working within a group, consider what you would need to know to test the suggested relationship between the pH and the performance of the product. List a series of questions that could be answered after doing some research.

6.1 Properties of Acids and Bases

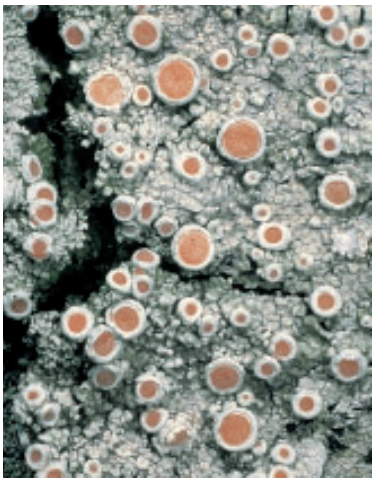

Figure 1
Lichen like this is used to make litmus.

Historically, only a few simple properties of acids and bases, such as their effect on the colour of litmus, were known by the middle of the 17th century (**Figure 1**). By the early 20th century, many other properties, such as pH, were discovered and new theories about acid–base reactions were created. Acids and bases are classes of compounds that have historically been distinguished by their empirical properties, primarily the behaviour of their aqueous solutions.

In general, science evolves from empirical knowledge to theoretical knowledge. In other words, to understand and explain acids and bases, scientists first need to have reliable empirical information about acids and bases before theories can be developed to explain them.

Technology that uses acids and bases depends on both empirical and theoretical knowledge of acids and bases for solving practical problems. The scientific knowledge of acids and bases is applied in several technological contexts: *consumer* (individuals), *commercial* (companies that use manufactured products to produce other products and processes), and *industrial* (large-scale companies that usually deal with raw materials and produce starting materials). Throughout this chapter, you will see examples of acids and bases used in each of these contexts.

INVESTIGATION 6.1 *Introduction*

Properties of Acids and Bases

In this investigation, you will use your previous knowledge of properties of substances, and practise your problem-solving skills. You are provided with solutions of approximately equal concentrations, at the same temperature, of the following pure substances: $CaCl_2(s)$, $C_3H_4OH(COOH)_3(l)$, $C_6H_{12}O_6(s)$, $Ca(OH)_2(s)$, $NH_3(g)$, $NaHSO_4(s)$, $CH_3OH(l)$, $H_2SO_4(l)$, $Na_2CO_3(s)$. Remember to include variables in your Design, and safety and disposal instructions in your Procedure.

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	● Materials	● Evaluation (1, 2, 3)
○ Hypothesis	● Procedure	
● Prediction	● Evidence	

Purpose

The purpose of this investigation is to test previous knowledge about the properties of acids and bases.

Problem

What properties are most useful for distinguishing acids and bases from other classes of compounds?

To perform this investigation, turn to page 260.

Learning Tip

Note that the terms "acid" and "base" refer to chemical substances, whereas the terms "acidic" and "basic" refer to the properties of a solution.

The Nature of Acidic and Basic Solutions

As shown in **Table 1**, acidic and basic solutions can be readily distinguished from each other by testing with an indicator (litmus) or pH paper (or meter). If you want to distinguish all four categories of solutes, a conductivity test would also be required.

Table 1 Diagnostic Tests for Various Types of Solutions

Type of solute	Type of solution	Conductivity	Litmus	pH
most molecular compounds	neutral	no	no effect	7
most ionic compounds	neutral	yes	no effect	7
acids	acidic	yes	blue to red	<7
bases	basic	yes	red to blue	>7

What is it about acids and bases that causes the change in the colour of an indicator or in values on a pH scale? Early attempts at a theory of acids and bases tended to focus on acids and ignore bases. Over time, several theories followed a cycle of creation, testing, acceptance, further testing, and eventual rejection. In this chapter, you will look briefly at a few early suggestions and at a more modern theory in the next chemistry course.

The idea that the presence of hydrogen gave a compound acidic properties started with Sir Humphry Davy in the early 1800s. A few decades later, Justus von Liebig expanded this theory to include the idea that acids are salts of hydrogen. According to his theory, acids could be thought of as *ionic compounds in which hydrogen had replaced the metal ion*. Liebig's theory, however, did not explain why many compounds containing hydrogen have neutral properties (such as CH_4) or basic properties (such as NH_3). In the late 1800s, Svante Arrhenius provided the first useful theoretical definition of acids and bases. *Acids are substances that ionize in aqueous solution to form hydrogen ions, and bases are substances that dissociate to form hydroxide ions in aqueous solution.* Although this theory has some drawbacks, as you will see later, it is still a widely used theory in many applications that require a simpler understanding of acids and bases.

For a long time, chemists have believed that acidic properties of a solution are related to the presence of hydrogen ions, whereas basic properties are related to the presence of hydroxide ions. The specific nature of the hydrogen ion in a solution has been the subject of much debate within the scientific community. Theoretical chemists thought that it was very unlikely that a hydrogen ion, which is a tiny proton with a very high charge-to-size ratio, could exist on its own in an aqueous solution. It is likely to bond strongly to polar water molecules. The first empirical evidence for this bonding was provided in 1957 by Paul Giguère at the Université Laval, Quebec, with his discovery of the existence of hydrated protons. The simplest representation of a hydrated proton is $H_3O^+(aq)$, commonly called the **hydronium ion** (**Figure 2**). A modern view of the nature of acidic and basic solutions is that hydronium ions are responsible for acidic properties and hydroxide ions are responsible for basic properties. The acidic or basic properties of a solution are most conveniently measured using paper test strips that have absorbed an indicator (such as litmus paper), but are most precisely measured using a pH meter.

Learning Tip

Chemists have known about some acids for hundreds of years. Because these acids are commonly known by familiar names, their IUPAC names are not often used:

Familiar name	IUPAC name
hydrochloric acid	aqueous hydrogen chloride
nitric acid	aqueous hydrogen nitrate
sulfuric acid	aqueous hydrogen sulfide
acetic acid	ethanoic acid

You should know these four acids by both names.

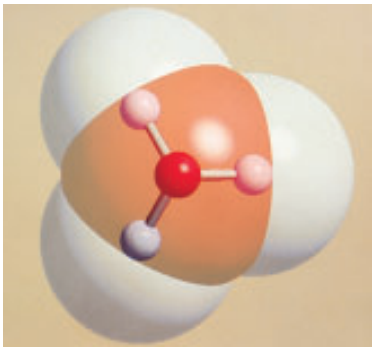

Figure 2
The hydronium ion has a trigonal pyramidal structure. The oxygen atom is the pyramid's apex; the hydrogen atoms form its base.

Section 6.1 Questions

1. In the usual progress of science, which comes first, empirical or theoretical knowledge?
2. List the three contexts that can be used to classify technological products or processes.
3. What is the most useful empirical property that can be used to distinguish acids, bases, and neutral compounds? Justify your answer.
4. How has the explanation of acidic properties changed from the early 1800s to the present day?
5. How is a hydronium ion different from a hydrogen ion? How is it similar?
6. Find and examine the label of one consumer product that contains an acid and one that contains a base. For each, identify any cautions noted for handling, storing, and disposing. Include the meaning(s) of any Household Hazardous Product symbols that indicate the primary hazard and the degree of hazard.
7. Environmental scientists and technicians often determine the acidity of aquatic environments.

Figure 3
Like other electronic devices, new pH meters are much smaller than earlier models. This one is very easy to take anywhere.

(a) Why is measuring pH with a meter, like the one in **Figure 3**, better than using an indicator such as litmus for this task?
(b) Which is the more common problem: acidic or basic aquatic environments? Briefly state your reasons for your answer.

6.2 pH and pOH Calculations

Acidic and basic solutions are an important part of many technological products, such as cleaning solutions, and of manufacturing processes, such as in the pulp and paper industry. In order to develop these technologies and deal with unintended consequences such as acid or base spills, a more detailed knowledge of these solutions is necessary.

At one time, the explanations of acidic and basic solutions were considered to be independent of one another—acidic solutions were explained by the presence of aqueous hydrogen ions (or the more modern concept of hydronium ions), whereas basic solutions were explained by the presence of aqueous hydroxide ions. Furthermore, the greater the concentration of hydronium ions is, the more acidic a solution is. Similarly, the higher the concentration of hydroxide ions is, the more basic a solution is.

You might expect that a neutral solution of pure water does not contain any hydronium or hydroxide ions. Careful testing, however, yields evidence that neutral water (pH 7) always contains trace amounts of both hydronium and hydroxide ions, due to a very slight ionization. In a sample of pure water, about two out of every billion molecular collisions are successful in forming hydronium and hydroxide ions.

$$2\,H_2O(l) \xrightarrow{\text{very slight}} H_3O^+(aq) + OH^-(aq)$$

In pure water at SATP, the hydronium ion concentration is very low: about 1×10^{-7} mol/L. This concentration is often negligible; for example, a conductivity test will show no conductivity for pure water unless the equipment is very sensitive (**Figure 1**).

Aqueous solutions exhibit a phenomenally wide range of hydronium ion concentrations—from more than 10 mol/L for a concentrated hydrochloric acid solution, to less than 10^{-15} mol/L for a concentrated sodium hydroxide solution. Any aqueous solution can be classified as acidic, neutral, or basic, using a scale based on the hydronium ion concentration.

At 25 °C, aqueous solutions can be classified as follows:

- neutral solution: $[H_3O^+(aq)] = 1 \times 10^{-7}$ mol/L
- acidic solution: $[H_3O^+(aq)] > 1 \times 10^{-7}$ mol/L
- basic solution: $[H_3O^+(aq)] < 1 \times 10^{-7}$ mol/L

Figure 1
A sensitive multimeter shows the electrical conductivity of distilled water in a laboratory. Successive distillations to increase purity will lower, but never eliminate, the conductivity of water as measured by increasingly sensitive instruments. (See Appendix C.3 for instructions on using a multimeter.)

The extremely wide range of hydronium ion concentration led to a convenient shorthand method of communicating these concentrations. In 1909, Danish chemist Søren Sørensen introduced the term pH or "power of hydrogen." The **pH** of a solution is defined as the negative of the exponent to the base ten of the hydronium ion concentration (expressed as moles per litre). This definition is not as complicated as it sounds. For example, a concentration of 10^{-7} mol/L has a pH of 7 (neutral), and a pH of 2 corresponds to a much greater hydronium ion concentration of 10^{-2} mol/L (acidic). Notice from these two examples that pH has no units, and that the definition of pH can be used to create the following equation:

$$[H_3O^+(aq)] = 10^{-pH}$$

The pH is often mentioned on the labels of consumer products such as shampoos (**Figure 2**); in water-quality tests for pools and aquariums; in environmental studies of acid rain; and in laboratory investigations of acids and bases. Since each pH unit corresponds to a factor of 10 in the concentration, the huge $[H_3O^+(aq)]$ range can now be communicated by a much simpler set of positive numbers (**Figure 3**). Changes in pH can be deceptive. For example, if you add some vinegar to pure water, the pH might change from 7 to 4. This change of 3 pH units does not appear very significant, but the change in hydronium ion concentration is 10^3 or 1000 times larger.

Contains a special Camomile
imported from Germany, so rich in
Levomenol, it's patented worldwide.
Instructions: Wet hair thoroughly. Apply
shampoo to work up a rich lather. Massage
scalp gently with fingertips. Repeat if desired
for maximum cleansing, thickening, brightening. Rinse thoroughly. PH-balanced for all hair
types.
FOR EXTERNAL USE ONLY
Keep out of reach of children. Test bleached or
tinted hair before using.

Figure 2
Some shampoos are pH balanced; that is, they have a pH similar to the natural pH of your scalp and hair (about 6.5). Do pH-balanced shampoos clean your hair as well as basic shampoos do?

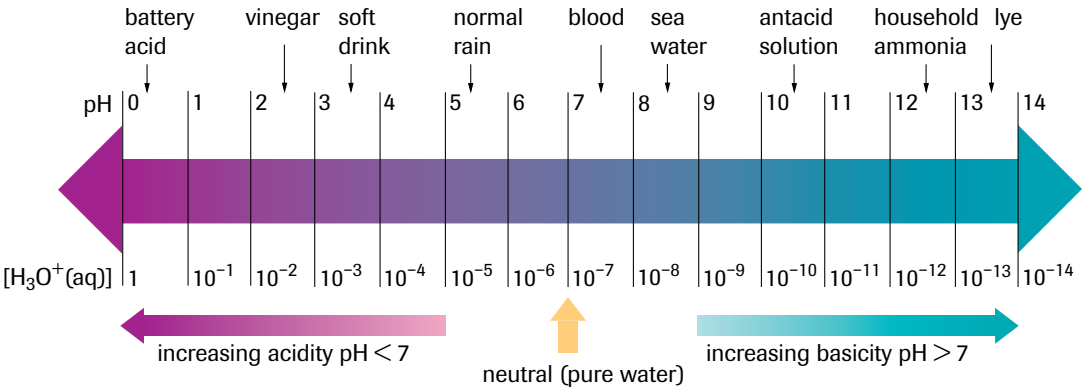

Figure 3
The pH scale is used to communicate a broad range of hydronium ion concentrations, in a wide variety of solutions. Most common acids and bases have pH values between 0 and 14.

Practice

1. Measurements of pH can be made using pH paper to provide a quick estimate of the hydronium ion concentration in an aqueous solution. What is the estimated hydronium ion concentration in each of the following solutions?
   (a) pure water: pH = 7
   (b) household ammonia: pH = 11
   (c) vinegar: pH = 2
   (d) soda pop: pH = 4
   (e) drain cleaner: pH = 14
2. Hydronium ion concentration is a theoretical concept used to explain the properties of acids. Express each of the following concentrations as pH values:
   (a) grapefruit juice: $[H_3O^+(aq)] = 10^{-3}$ mol/L
   (b) rainwater: $[H_3O^+(aq)] = 10^{-5}$ mol/L
   (c) milk: $[H_3O^+(aq)] = 10^{-7}$ mol/L
   (d) soap: $[H_3O^+(aq)] = 10^{-10}$ mol/L
3. If one water sample test shows a pH of 3 and another sample shows a pH of 5, by what factor do their hydronium ion concentrations differ? Justify your answer.

DID YOU KNOW ?

The "p" in pH

pH was developed only about 100 years ago, but already the origin of the term has become blurred. Some scientists associate pH with **p**ower of **h**ydrogen, H; others with **p**otential of **h**ydrogen. Sørensen was Danish, so perhaps the "p" in pH comes from the Danish word "potenz," meaning "strength," or the French word "potentiel." It is strange that we have so quickly lost the origin of such a familiar term.

LAB EXERCISE 6.A

The Relationship between pH and Hydronium Ion Concentration

Understanding pH and hydronium ion concentration is important in chemistry and also in the application of pH to other topics, such as environmental effects of pollution and consumer products. In the Analysis, use a spreadsheet program to produce the graphs.

Purpose

The purpose of this investigation is to create a relationship between the magnitude changes in pH and the changes in hydronium ion concentration of a solution.

Problem

What is the relationship between pH and hydronium ion concentration?

Design

A stock solution of hydrochloric acid is successively diluted and the pH of each diluted solution is measured using a calibrated pH meter. The manipulated variable is the concentration of hydrochloric acid (which equals the hydronium ion concentration). The responding variable is the pH. Some key controlled variables are temperature and type of acid used.

Evidence

Table 1 pH Readings of HCl(aq) Dilutions

$[H_3O^+(aq)]$ (mol/L)	pH
1.0×10^{-1}	0.9
1.0×10^{-2}	1.8
1.0×10^{-3}	2.8
1.0×10^{-4}	3.7
1.0×10^{-5}	4.9

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ○ Evidence
- ● Analysis
- ○ Evaluation

Analysis

(a) Enter the values from **Table 1** into a spreadsheet. To enter scientific notation, use "E" to represent "× 10". For example, enter 1.0×10^{-1} as 1E-1. Plot a graph of pH versus $[H_3O^+(aq)]$.
(b) In words, describe the relationship shown by this graph.
(c) In a blank section of the spreadsheet, create a new table by converting $[H_3O^+(aq)]$ to a logarithm of $[H_3O^+(aq)]$ and keeping pH the same. To enter the logarithm, use log10( ). For example, enter the data in the first row of Table 1 as log10(1E-1) and 0.9. Plot a graph of pH versus log ($[H_3O^+(aq)]$).
(d) In words, describe the relationship shown by this graph. What is unusual about this graph?
(e) Alter your table of values by placing a negative sign in front of each log term. For example, enter the data in the first row of Table 1 as -log10(1E-1) and 0.9. The graph will change as you alter each number.
(f) In words, describe this new graph. Why is this graph simpler and better than any of the previous graphs?

CAREER CONNECTION

Ecologist

Ecologists conduct field research to study land, water, plant, and animal interactions, and make recommendations for environmental impact assessments. Some ecologists specialize in marine biology, microbiology, or ecosystem management, among other things. Most of us care about environmental impacts, so find out more about becoming an ecologist.

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pH Calculations

Previously, pH was defined as the negative of the exponent to the base 10 of the hydronium ion concentration (expressed as moles per litre). This simplified definition is useful only if the pH values are integers and the concentration values are simply powers of 10. This situation is rarely the case. When environmental scientists or ecologists measure the pH of aquatic environments, they often require pH measurements to one or more decimal places.

The definition needs to be improved to be able to convert pH values such as 5.3 to a hydronium ion concentration, and hydronium ion concentrations such as 6.7×10^{-8} mol/L to a pH. Expressed as a numerical value without units, the pH of a solution is best defined as the negative of the logarithm to the base 10 of the hydronium ion concentration:

$$\mathbf{pH = -\log[H_3O^+(aq)]}$$

SAMPLE problem 6.1

Given a hydronium ion concentration of 6.7×10^{-8} mol/L, calculate the pH.

According to the definition, $pH = -\log[H_3O^+(aq)]$, the pH is calculated as

$$pH = -\log(6.7 \times 10^{-8})$$

Notice that the units have been dropped because a logarithm has no units. When you enter the concentration value into your calculator and press "log," the number −7.1739252 appears (some calculators may display extra digits), which means

$$pH = -(-7.1739252)$$

The purpose of the negative sign in the pH definition is to change the initial "log" value from a negative to a positive value. Now, how many of the digits displayed on the calculator are significant? The answer to this question lies in the certainty (number of significant digits) of the concentration; 6.7×10^{-8} mol/L shows two significant digits. For the same reason that the exponent "8" in the concentration does not count as a significant digit, the integer part of the pH is also not counted. The correct answer is a pH of 7.17. *The number of digits following the decimal point in the pH value is equal to the number of significant digits in the hydronium ion concentration.* If you write the concentration in a nonstandard exponential notation, this rule may be clearer:

$[H_3O^+(aq)] = 0.67 \times 10^{-7}$ mol/L [two significant digits]

$pH = 7.17$ [two decimal places]

COMMUNICATION example 1

Communicate a hydronium ion concentration of 4.7×10^{-11} mol/L as a pH value.

Solution

$$pH = -\log[H_3O^+(aq)]$$
$$= -\log(4.7 \times 10^{-11})$$
$$= 10.33$$

The pH of the solution is 10.33.

When pH is measured using a pH meter or pH paper in a chemical analysis, you may need to convert from pH to the amount concentration of hydronium ions. This conversion is based on the mathematical concept that a base 10 logarithm represents an exponent:

$$[H_3O^+(aq)] = 10^{-pH}$$

Notice that this definition is the same as that initially given for pH, but now it is more general and applies to all pH values, not only integers. Using this relationship, you can convert from a pH to a hydronium ion concentration. Because a pH (logarithm) has no units and the definition of pH includes the requirement that the concentration be in moles per litre, you will *always* need to add the units, mol/L, to your answer.

Learning Tip

Numbers in scientific notation are best entered on your calculator using the exponent (EE or EXP) key; for example, 8.7 EE −9. The calculator is programmed to treat this entry as one value. The 10^x key is not recommended because you may obtain incorrect results in some situations and on some calculators.

Learning Tip

Use your calculator to do the calculation shown in Communication Example 1. For common graphing calculators, the sequence of keystrokes is likely as follows:

(−) LOG 4 • 7

2nd , (−) 1 1

ENTER

For scientific calculators, the number (4.7 EE −11) is entered first, followed by the function (log) and then the sign change (+/−).

BIOLOGY CONNECTION

pH Dependence

Many biological processes, such as enzyme reactions, depend on pH. If you are taking a biology course, you will see several examples of pH dependent processes.

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Figure 4
A pH meter measures a tiny voltage produced by a solution containing hydronium ions and converts this electrical measurement into a pH reading.

Learning Tip

Use your calculator to do the calculation shown in Communication Example 2. For common graphing calculators, the sequence of keystrokes is likely as follows:

2nd | LOG | (-) | 1 | 0 | • | 3 | 3 | ENTER

For scientific calculators, the number (−10.33) is entered first, followed by the function (10^x).

SAMPLE problem 6.2

A solution has a pH of 5.3 (**Figure 4**). Calculate its hydronium ion concentration.

According to the definition, $[H_3O^+(aq)] = 10^{-pH}$, the hydronium ion concentration is calculated as

$$[H_3O^+(aq)] = 10^{-5.3} \text{ mol/L}$$

Note that the units have been added. Strictly speaking, this answer is mathematically correct, but it is not communicated in the usual or expected format. Your calculator will change the format of this answer into a properly expressed number. When you enter $10^{-5.3}$ on a calculator, you will obtain

5.01187 E −6 or 5.01187 −06 (which is 5.01187×10^{-06}).

Recall from Sample Problem 6.1 that the number of digits following the decimal point in the pH value is equal to the number of significant digits in the hydronium ion concentration. In the case of a pH equal to 5.3, one digit following the decimal point means one significant digit in the answer, 5×10^{-6} mol/L. If we write the concentration in a nonstandard exponential notation, this rule may be clearer:

$[H_3O^+(aq)] = 0.5 \times 10^{-5}$ mol/L [one significant digit]

pH = 5.3 [one decimal place]

COMMUNICATION example 2

Communicate a pH of 10.33 as a hydronium ion concentration.

Solution

$$[H_3O^+(aq)] = 10^{-pH}$$
$$= 10^{-10.33} \text{ mol/L}$$
$$= 4.7 \times 10^{-11} \text{ mol/L}$$

The hydronium concentration is 4.7×10^{-11} mol/L.

Practice

4. State the rule for relating the certainty (number of significant digits) of a hydronium ion concentration to a pH measurement.
5. Knowing the pH of common substances is useful to a wide variety of people such as nutritionists, medical personnel, environmentalists, and consumers. Express each of the following concentrations as pH values.
   (a) grapefruit juice: $[H_3O^+(aq)] = 2.1 \times 10^{-3}$ mol/L
   (b) rainwater: $[H_3O^+(aq)] = 1 \times 10^{-5}$ mol/L
   (c) milk: $[H_3O^+(aq)] = 2.50 \times 10^{-7}$ mol/L
   (d) soap: $[H_3O^+(aq)] = 7.3 \times 10^{-9}$ mol/L
6. The technology of a pH meter provides an efficient way to obtain a pH that various people, such as chemists and biologists, often convert to a concentration. Calculate the hydronium ion concentration in each of the following household mixtures.
   (a) ammonia cleaner: pH = 11.3
   (b) salad dressing: pH = 2.65
   (c) carbonated drink: pH = 4.2
   (d) oven cleaner: pH = 13.755
7. As a result of an industrial accident, the concentration of hydronium ions in a small lake decreased one thousand times. How did the pH change? Did it increase or decrease?
8. What class of hazard and safety symbol is used on bottles of acids and bases? State the class letter and name, and describe or draw the symbol.

pOH and Hydroxide Ion Concentration

Although pH is used more commonly, in some applications, it may be more practical or convenient to describe hydroxide ion concentrations in a similar way. The definition of pOH follows the same format and the same certainty rule as pH. The **pOH** of a solution is the negative of the logarithm to the base 10 of the hydroxide ion concentration. Similarly, the hydroxide ion concentration is the negative of the exponent to the base 10 of the pOH:

$$\mathbf{pOH = -\log[OH^-(aq)]} \text{ and } \mathbf{[OH^-(aq)] = 10^{-pOH}}$$

COMMUNICATION example 3

The hydroxide ion concentration of a cleaning solution is determined to be 0.27 mol/L. What is its pOH?

Solution

$$\begin{aligned} \text{pOH} &= -\log[\text{OH}^-(\text{aq})] \\ &= -\log(0.27) \\ &= 0.57 \end{aligned}$$

The pOH of the cleaning solution is 0.57.

COMMUNICATION example 4

A sample of tap water has a pOH of 6.3. Calculate the hydroxide ion concentration.

Solution

$$\begin{aligned} [\text{OH}^-(\text{aq})] &= 10^{-\text{pOH}} \\ &= 10^{-6.3} \text{ mol/L} \\ &= 5 \times 10^{-7} \text{ mol/L} \end{aligned}$$

The hydroxide ion concentration of the tap water is 5×10^{-7} mol/L.

Practice

9. A 4.5 mol/L solution of sodium hydroxide is prepared to clean a clogged drain. Calculate the pOH of this solution.

10. Soybean curd or tofu is one of the few foods that are basic. What is the hydroxide ion concentration in tofu if its pOH is 6.80?

11. The term "pH" is used in various technological contexts as well as in scientific fields of study. The term "pOH" seems to be used primarily in chemistry courses and materials. Suggest a reason for this practice.

WWW WEB Activity

Web Quest—Bad Hair Day?

Scientific research and technological developments are important in the development of hair products. Does pH matter? Many companies would like you to believe that it does.

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DID YOU KNOW?

Other Log Scales

The Richter scale for earthquakes is a log scale. An earthquake of magnitude 6 releases ten times as much energy as one of magnitude 5.

Another common example of a log scale is the decibel scale for sound intensity. Every change of 10 dB (decibels) corresponds to a change of 100 in the sound intensity (power per square metre), but for the average human, this difference is perceived as a change of a factor of two in the "loudness." So, a rock concert measured at 120 dB has a million times the intensity and sixty-four times the loudness of a normal conversation level of 64 dB.

SUMMARY pH and pOH

$$pH = -\log[H_3O^+(aq)] \qquad pOH = -\log[OH^-(aq)]$$

$$[H_3O^+(aq)] = 10^{-pH} \qquad [OH^-(aq)] = 10^{-pOH}$$

- The number of digits following the decimal point in a pH or pOH value is equal to the number of significant digits in the corresponding hydronium or hydroxide ion concentration.
- For both pH and pOH, an inverse relationship exists between the ion concentration and the pH or pOH. For example, the greater the hydronium ion concentration, the lower the pH.

Section 6.2 Questions

1. Describe the main evidence that pure water contains hydronium and hydroxide ions.
2. What are some advantages of using pH compared to using the hydronium ion concentration?
3. Food scientists and dieticians measure the pH of foods when they devise recipes and special diets.
   (a) Copy and complete **Table 2**.
   (b) Based on pH only, predict which of the foods would taste most sour.

Table 2 Acidity of Foods

Food	$[H_3O^+(aq)]$ (mol/L)	pH
oranges	5.5×10^{-3}	
asparagus		8.4
olives		3.34
blackberries	4×10^{-4}	

4. If the pH is measured to be 0.0, is the hydronium ion concentration zero? Justify your answer.
5. The usefulness of many cleaning products depends, in part, on their basic nature.
   (a) Copy and complete **Table 3**.
   (b) Rank the products from least to most basic.
   (c) What safety precautions should you follow in handling acids and bases?

Table 3 Cleaning Products

Cleaning Solution	$[OH^-(aq)]$ (mol/L)	pOH
stain remover	6.7×10^{-2}	
baking soda		5.0
bleach	2.5×10^{-3}	
drain cleaner		0.1

6. An HCl(aq) solution with $[H_3O^+(aq)]$ of 1.0×10^{-2} mol/L is diluted by a factor of 1000. Determine the new pH.
7. Sketch a pOH scale similar to the pH scale (Figure 3, page 239). Label hydroxide ion concentrations in powers of 10, pOH, neutral point, and regions of acidic and basic solutions. (Examples are not required.)
8. If an acidic solution with a pH of 4 is completely neutralized, by what factor will the hydronium ion concentration change? Will it increase or decrease?
9. Most common acids and bases have a pH that falls in the range of 0 to 14. This range does not mean that other values do not exist. Calculate the pH of each of the following solutions.
   (a) a concentrated acid that has a hydronium ion concentration of 10 mol/L
   (b) a concentrated base that has a hydronium ion concentration of 1.6×10^{-15} mol/L
10. Design an experiment to determine if the vinegar from a fast-food outlet is normal household vinegar or diluted vinegar. State any controlled variables.
11. A scientist wants to determine the pH of several toothpastes, but must add water to the pastes in order to measure their pH with a pH meter. Critique this experimental design by supporting and defending the design, and by suggesting an alternative design.
12. Provide several examples of consumer products that have a relatively low pH and some that have a relatively high pH.

Extension

13. Research the effect of soil pH on deciduous versus evergreen plants. Report this information in a short margin note for a gardening magazine.

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14. What is the normal pH range of human blood? If blood becomes too acidic, what symptoms appear? Can blood become too basic? If so, what happens? In both cases (when blood is too acidic or too basic), what medical technology is available to treat the problem?

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Acid–Base Indicators 6.3

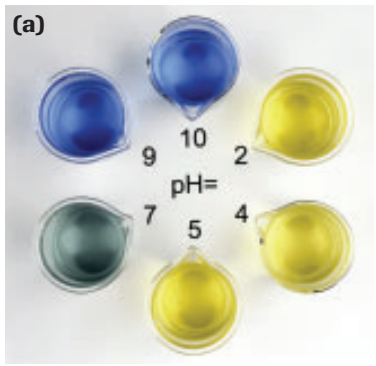
A number of synthetic dyes and compounds found in plants change colour when mixed with solutions of an acid or a base (**Figure 1**). Substances that change colour when the acidity of the solution changes are known as **acid–base indicators**. A very common indicator used in school laboratories is litmus, which is obtained from a lichen (see Figure 1, page 236). Litmus paper is prepared by soaking absorbent paper with litmus solution and then drying it. As you know, red and blue are the two colours of the litmus dye—red for acidic solutions and blue for basic solutions. Bromothymol blue and phenolphthalein are two other commonly used indicators (**Figure 2**).

Acid–base indicators are unique chemicals because they can exist in at least two forms, each with a distinctly different colour. The form of the chemical depends on the acidity of the solution. Acid–base indicators have very complicated molecular structures and formulas. Since it is inconvenient to write the actual formula, simple abbreviations are used instead. For example, litmus is abbreviated "Lt," bromothymol blue is "Bb," and "In" is a generic symbol for any indicator. The two forms of any indicator depend on whether a particular hydrogen atom is present in the indicator's molecule. In general, the lower pH form of the indicator is designated as "HIn(aq)" and the higher pH form as "In^-(aq)." Because the chemical structure of each indicator is different, the pH at which the indicator changes from the HIn(aq) form, with one colour, to the In^-(aq) form, with another colour, is different for each indicator.

Let's look more closely at litmus as an example. According to the table of acid–base indicators (see the inside back cover of this textbook), litmus changes colour between a pH of 6.0 and 8.0, which means that litmus is red at any pH less than or equal to 6.0 and is blue at any pH greater than or equal to 8.0 (**Figure 3**). Between 6.0 and 8.0, litmus is in the process of changing colour and you will see mixtures of red and blue. These intermediate colours are generally not useful, with the common exception of bromothymol blue, where an equal mixture of yellow and blue produces a distinct green in the middle of the pH range for this indicator (**Figure 2(a)**). The colours and pH of many other indicators have been measured and are reported in the table of acid–base indicators on the inside back cover of this textbook.

Acid–base indicators have two primary uses. As you will see in Chapter 8, Chemical Analysis, indicators are commonly used to mark the end of a titration. The other use that you will investigate below is to estimate the pH of a solution by using a number of different indicators. In this method, acid–base indicators are used to replace the more expensive pH meter, even though indicators are not as accurate.

Figure 1
The test tubes show the colour of purple cabbage juice in solutions with different pHs, in order from left to right: 14, 9, 7, 4, and 1.



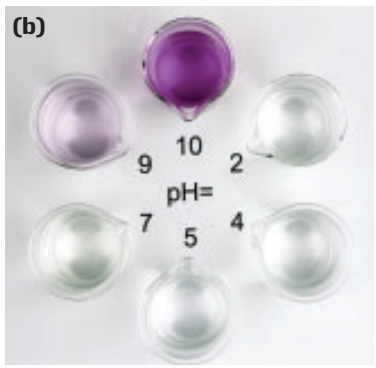


Figure 2
Colour changes of common acid–base indicators
(a) bromothymol blue
(b) phenolphthalein

Figure 3
The colour changes of litmus are a little more complicated than what you have learned previously. There is a "fuzzy" region around the neutral point (pH = 7) where the colour is not easily distinguished. It is outside of this region where litmus is either definitely red (pH ≤ 6 in acidic solutions) or definitely blue (pH ≥ 8 in basic solutions).

CAREER CONNECTION

Medical Laboratory Technologist

Medical laboratory technologists assist physicians in diagnosing and treating patients. They examine body fluids and tissues for the presence of disease. They can also specialize in transfusion medicine, or the microscopic examination of other types of cells and tissues. These diagnostic specialists are essential medical professionals.

Explore further to find out details on medical laboratory technologists, including where they are employed in your community and province.

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SAMPLE problem 6.3

Separate samples of an unknown solution were individually tested with several indicators. The solution containing methyl red turned red; the solution with thymol blue turned yellow; and the solution with methyl orange turned red. What is the most likely pH of the solution?

Refer to the table of acid–base indicators (inside back cover of the textbook).

- If methyl red turned red, then the pH must be ≤ 4.8.
- If thymol blue turned yellow, then the pH must be between 2.8 and 8.0. Notice that thymol blue is unusual because it has two colour changes over the normal pH range: yellow would mean a pH ≥ 2.8, but ≤ 8.0.
- If methyl orange turned red, then the pH must be ≤ 3.2.

Combining these results, the pH must be between 2.8 and 3.2. The hydronium ion concentration can then be calculated from your estimated pH, if required. This example shows that it is relatively simple and possible to determine the pH down to a small range, but this method is generally not as accurate as using a pH meter.

COMMUNICATION example

In chemical analysis of separate samples of an unknown solution, phenolphthalein was colourless, bromothymol blue was blue, and phenol red was red. What is the estimated pH and hydronium ion concentration?

Solution

Indicator	Colour	pH
phenolphthalein	colourless	≤ 8.2
bromothymol blue	blue	≥ 7.6
phenol red	red	≥ 8.0

The pH is likely 8.1.

$$[H_3O^+(aq)] = 10^{-8.1} \text{ mol/L}$$
$$= 8 \times 10^{-9} \text{ mol/L}$$

The hydronium ion concentration is likely 8×10^{-9} mol/L.

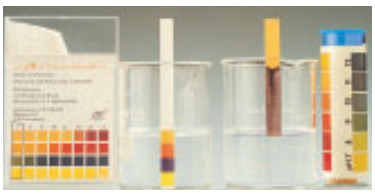

Figure 4
Comparing the colours of the test strip after dipping it into solution with the colours of the scale on the container gives an approximate pH. The inexpensive pH paper on the right bleeds (colour runs down the paper).

pH Test Strips

Litmus is not the only indicator paper available. Bromothymol blue paper is sold to test aquarium water for pH values between 6.0 and 7.6, to a precision of about 0.1 pH unit. This precision is possible because subtle differences in colour over the range in which bromothymol blue changes can be matched to a colour comparison chart. Other test strips contain several different indicators and show different colours at different pH values. These test strips give a composite colour that can measure pH from 0 to 14 to within one to two pH units (**Figure 4**).

mini Investigation pH of a Solution

In this activity, you will design an experiment to challenge your fellow students. Imagine that you have a solution with a pH known only to you. How can you give clues about its pH?

Materials: index cards or paper

- On one side of the card, write the pH of your solution.
- On the other side, write the names and colours (at that pH) of three or four indicators.
- Hand your card, "indicator" side up, to another student. See how close he or she can come to determining the pH of your solution without looking at the answer.

LAB EXERCISE 6.B

Using Indicators to Determine pH

One Design for determining the pH of a solution is testing the solution with indicators. Include a table of indicators and pH as part of your Analysis.

Report Checklist

○ Purpose	○ Design	● Analysis
○ Problem	○ Materials	○ Evaluation
○ Hypothesis	○ Procedure	
○ Prediction	○ Evidence	

Purpose

The purpose of this lab exercise is to use the concept of acid–base indicators and the reference table of indicator colours to determine the pH of three different solutions.

Problem

What is the approximate pH of three solutions?

Design

The solutions were labelled A, B, and C. Samples of each solution were tested with different indicators.

Evidence

Solution A: After addition to samples of the solution, methyl violet was blue, methyl orange was yellow, methyl red was red, and phenolphthalein was colourless.

Solution B: After addition to samples of the solution, indigo carmine was blue, phenol red was yellow, bromocresol green was blue, and methyl red was yellow.

Solution C: After addition to samples of the solution, phenolphthalein was colourless, thymol blue was yellow, bromocresol green was yellow, and methyl orange was orange.

SUMMARY *Acid–Base Indicators*

- Acid–base indicators are substances that change colour when the acidity of the solution changes.
- Acid–base indicators are unique chemicals because they can exist in at least two forms, each with a distinctly different colour. In general, the lower pH form of the indicator is "HIn(aq)" and the higher pH form is "In^-(aq)".
- The pH of a solution can be determined by comparing the resulting colours of several indicators in the solution with an indicator chart.

Section 6.3 Questions

1. According to the table of acid–base indicators on the inside back cover, what is the colour of each of the following indicators in the solutions of given pH?
(a) phenolphthalein in a solution with a pH of 11.7
(b) bromothymol blue in a solution with a pH of 2.8
(c) litmus in a solution with a pH of 8.2
(d) methyl orange in a solution with a pH of 3.9

2. Complete the Analysis for each of the following diagnostic tests. If the specified indicator is added to a solution, and the solution turns the given colour, then the solution's pH is __.
(a) methyl red (red)
(b) alizarin yellow (red)
(c) bromocresol green (blue)
(d) bromothymol blue (green)

3. Separate samples of a solution turned methyl orange and bromothymol blue indicators yellow, and a bromocresol green indicator blue.
(a) Estimate the pH of the solution.
(b) Calculate the approximate hydronium ion concentration of the solution.

4. Solving puzzles is a common feature of the scientific enterprise. Science and technology olympics often assign puzzles similar to this one: Design an experiment that uses indicators to identify which of three solutions, labelled X, Y, and Z, have pH values of 3.5, 5.8, and 7.8. There are several acceptable designs for this problem.

Extension

5. Measurement of pH is used in consumer, commercial, and industrial contexts. Make a list of different examples in which pH is likely used for each context. What different technologies exist for measuring pH, and how would the technology change with the context?

6. Using some of the concepts from Appendix B.4, design an experiment to test the role of pH in hair shampoos.

6.4 Explaining Acids and Bases

Learning Tip

Acids can have a variety of names, including classical and IUPAC names. For a review of acid nomenclature, see Section 1.6, in the Chemistry Review Unit.

In 1887, Svante Arrhenius introduced the first comprehensive theory of aqueous solutions. You have already seen his ideas about dissociation and ionization (Chapter 5, page 197). According to Arrhenius, ionic compounds dissociate into separate cations and anions when they dissolve to form a solution:

ionic compound $\rightarrow$ cation + anion

e.g., $LiCl(s) \rightarrow Li^+(aq) + Cl^-(aq)$

Arrhenius proposed that bases are soluble ionic compounds that dissociate into a cation and the hydroxide ion, an anion:

base $\rightarrow$ cation + $OH^-(aq)$

e.g., $LiOH(s) \rightarrow Li^+(aq) + OH^-(aq)$

Acids, according to Arrhenius, ionize in water to produce hydrogen ions plus an anion.

acid $\rightarrow$ $H^+(aq)$ + anion

e.g., $HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$

Arrhenius did not know that a hydrogen ion is better described as a hydronium ion—a hydrogen ion bonded to a water molecule. This discovery came much later. Nevertheless, it does not change his theory substantially because the "(aq)" part of $H^+(aq)$ can easily be interpreted to refer to some water molecule in the solvent.

Scientific knowledge is always subject to change. New evidence may arise unexpectedly or from the specific testing of generalizations, laws, and theories. If the new evidence supports the generalization, law, or theory, it strengthens existing support for it. If the new evidence contradicts the generalization, law, or theory, then changes are usually required.

INVESTIGATION 6.2 *Introduction*

Testing Arrhenius' Acid–Base Definitions

In this investigation, you will use Arrhenius' acid–base theory to make predictions, test these predictions using diagnostic tests, and finally, evaluate Arrhenius' theory. For simplicity, assume that Arrhenius' theory restricts dissociation and ionization to only two ions. In your Design, be sure to identify all variables, including any controls.

Purpose

The purpose of this investigation is to test Arrhenius' definitions of an acid and a base.

To perform this investigation, turn to page 260.

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	○ Materials	● Evaluation (1, 2, 3)
○ Hypothesis	● Procedure	
● Prediction	● Evidence	

Problem

Which of the substances tested may be classified as an acid, a base, or neutral, using Arrhenius' definitions?

A Revision of Arrhenius' Definitions

Evidence from Investigation 6.2 clearly indicates the limited ability of Arrhenius' definitions to predict acidic or basic properties of a substance in aqueous solution. Only five predictions that can reasonably be made using Arrhenius' definitions are verified: the acids are $HCl(aq)$ and $CH_3COOH(aq)$, the bases are $NaOH(aq)$ and $Ca(OH)_2(aq)$, and

the neutral solution is $NaNO_3(aq)$. Seven predictions were falsified. There were problems predicting the properties of solutions of compounds of polyatomic anions containing hydrogen, such as $NaHCO_3(aq)$ and $NaHSO_4(aq)$; solutions of oxides of metals and nonmetals, such as $CaO(aq)$ or $CO_2(aq)$; basic solutions that contain neither oxides nor hydroxides, such as $NH_3(aq)$ and $Na_2CO_3(aq)$; and acidic solutions such as $Al(NO_3)_3(aq)$. Each of these substances fails to produce a neutral solution, as Arrhenius' definition would predict. Therefore, the theoretical definitions of acid and base need to be revised or replaced.

The ability of a theoretical concept to explain evidence is not valued as much as its ability to predict the results of new experiments. The best theories not only explain what is known, but enable correct predictions about new observations. Revising Arrhenius' acid–base definitions to explain the results of Investigation 6.2 involves two key ideas: (1) collisions of dissolved substances with water molecules and (2) the nature of the hydrogen ion. Because all substances tested are in aqueous solution, then particles will constantly be colliding with, and may also react with, the water molecules present.

The formation of acidic solutions by HCl may now be explained as a reaction with water molecules, resulting in hydronium ions being formed (**Figure 1**):

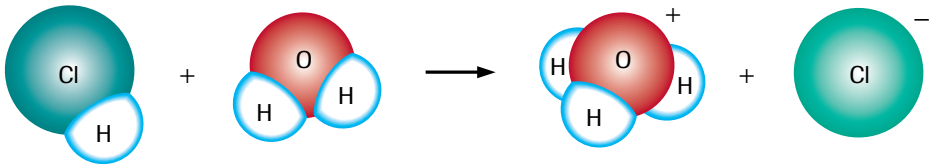

Figure 1
When gaseous hydrogen chloride dissolves in water, the HCl molecules are thought to collide and react with water molecules to form hydronium ions and chloride ions.

$$HCl(aq) + H_2O(1) \rightarrow H_3O^+(aq) + Cl^-(aq)$$

The idea of particles reacting with water produces some immediate improvements to Arrhenius' theory. First, Arrhenius could not explain how or why an acid molecule "falls apart" when it ionizes. Now, this reaction becomes like other chemical reactions—a collision between particles. Second, this idea includes the modern evidence for a hydronium ion (hydrated hydrogen ion) in a logical, balanced chemical equation.

Other substances whose solutions were found to be acidic can be explained in a similar way using this modified Arrhenius theory. For example, a solution of the hydrogen sulfate ion was shown to be acidic, and can be explained as a simple dissociation of sodium hydrogen sulfate into individual ions and then a reaction of the hydrogen sulfate ion with water:

$$NaHSO_4(s) \rightarrow Na^+(aq) + HSO_4^-(aq)$$

$$HSO_4^-(aq) + H_2O(1) \rightarrow H_3O^+(aq) + SO_4^{2-}(aq)$$

According to this modified Arrhenius theory, **acids** are substances that react with water to produce hydronium ions.

Reaction with water is also necessary to explain the behaviours of most bases. The main characteristic of bases is the production of hydroxide ions in solution. According to Arrhenius' original theory, bases produce hydroxide ions in solution by simple dissociation. For example:

$$Ca(OH)_2(s) \rightarrow Ca^{2+}(aq) + 2\,OH^-(aq)$$

In this example, there is no need to show a reaction with water because hydroxide ions are present as a result of the dissociation. As you have seen in Investigation 6.2, however, there are many other substances that are considered bases. For example, according to the evidence, ammonia and sodium carbonate form basic aqueous solutions. Arrhenius' theory did not help you to predict this result; nor does it explain this evidence. The

Learning Tip

The sodium ion is eliminated as a possible factor in acidic or basic solutions because many sodium compounds (e.g., NaCl(aq))—like all Group 1 ions—form neutral (pH 7) solutions.

modified Arrhenius theory—the reaction-with-water theory—can explain the evidence, as illustrated in the chemical equations below:

$$NH_3(aq) + H_2O(l) \rightarrow OH^-(aq) + NH_4^+(aq)$$

Ammonia is considered a base because it produces hydroxide ions in solution. Sodium carbonate is an ionic compound with high solubility that dissociates in water to provide aqueous ions of sodium and carbonate. The basic character of carbonate ion solutions can also be explained as a reaction with water to produce hydroxide ions:

$$Na_2CO_3(s) \rightarrow 2\,Na^+(aq) + CO_3^{2-}(aq)$$

$$CO_3^{2-}(aq) + H_2O(l) \rightarrow OH^-(aq) + HCO_3^-(aq)$$

According to the modified Arrhenius theory, most **bases** are substances that react with water to produce hydroxide ions. Of course, if the base already contains hydroxide ions, a simple dissociation produces the hydroxide ions directly, as in calcium hydroxide.

EXTENSION

CBC radio ONE

QUIRKS & QUARKS

Oceans and CO_2

What is the effect of the increasing concentration of atmospheric carbon dioxide on the oceans? Researchers are investigating how the changing pH appears to be interfering with the growth of the shells of marine snails.

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DID YOU KNOW ?

Use of Theories

Chemists do not always use the most modern theories. As long as the essential idea is the same, different levels of theories are used in different applications. For example, the behaviour of acids in solution can be explained as either an ionization to produce hydrogen ions or a reaction with water to produce hydronium ions, depending on the context and level of sophistication required.

SUMMARY Writing Chemical Equations Using the Modified Arrhenius Theory

1. Write the chemical formulas for the reactants: molecule or polyatomic ion + water.
   - Ignore any Group 1 and 2 cations, and Group 7 anions in the compound formula. Evidence from many compounds shows that these ions do not produce acidic or basic solutions.
   - If the substance is a nonmetal oxide (e.g., $CO_2(g)$, $SO_2(g)$), use two moles of water for every mole of the substance in the reactants.
2. Note the evidence provided. If the final solution is acidic, write hydronium ions as the first product. If the final solution is basic, then hydroxide ions are the first product.
3. Complete the other product by determining the combination of atoms and charge required to balance the chemical equation.
   - The other product should be a recognizable chemical formula—usually a polyatomic ion on your polyatomic ion chart (see the inside back cover).

COMMUNICATION example 1

In a test of the modified Arrhenius theory, a student tested the pH of a solution made by dissolving solid sodium cyanide in water, and found it to have a pH greater than 7. Can the modified Arrhenius theory explain this evidence? Provide your reasoning.

Solution

$$NaCN(s) \rightarrow Na^+(aq) + CN^-(aq)$$

$$CN^-(aq) + H_2O(l) \rightarrow OH^-(aq) + HCN(aq)$$

The modified Arrhenius theory can explain the basic character of a sodium cyanide solution because it is possible to write a balanced chemical equation with valid products, including the hydroxide ion.

COMMUNICATION example 2

Carbon dioxide is a major air pollutant from the combustion of fossil fuels. Suggest a possible chemical reaction that explains the acidity of a carbon dioxide solution.

Solution

$$CO_2(g) + 2\,H_2O(l) \rightarrow H_3O^+(aq) + HCO_3^-(aq)$$

Practice

1. Use the modified Arrhenius theory to suggest a chemical reaction equation to explain the acidic properties of each of the following solutions:
   (a) HI(aq) (b) HOCl(aq) (c) $H_3PO_4(aq)$
2. Where possible, use the modified Arrhenius theory to explain the basic properties of each of the following solutions. Include appropriate chemical reaction equations:
   (a) $Na_2SO_4(aq)$ (b) $NaCH_3COO(aq)$ (c) $Sr(OH)_2(aq)$

Scientists regard a theory as acceptable only if it can correctly predict results in new situations. The revisions made to Arrhenius' theoretical definitions do not offer reasons for these reactions, nor do they supply predictions in many situations. In other words, once you know the answer, you can usually explain it using the modified Arrhenius theory. Predicting the correct answer is always more difficult for any theory. Consider a solution formed by dissolving sodium hydrogen phosphate in water.

$$Na_2HPO_4(s) \rightarrow 2\,Na^+(aq) + HPO_4^{2-}(aq)$$

Will the solution be acidic, basic, or neutral? We can write valid equations to predict that either hydronium ions or hydroxide ions will form when hydrogen phosphate ions react with water:

$$HPO_4^{2-}(aq) + H_2O(l) \rightarrow H_3O^+(aq) + PO_4^{3-}(aq)$$

or $$HPO_4^{2-}(aq) + H_2O(l) \rightarrow OH^-(aq) + H_2PO_4^-(aq)$$

Nothing that you have studied so far in this textbook enables you to *predict* which of these equations is correct. If you know that the solution turns red litmus blue, however, then you can select one of the equations to *explain* the evidence. Clearly, the modified Arrhenius theory still needs some improvements.

Neutralization Reaction

You are familiar with the double replacement reaction generalization, which includes mostly precipitation reactions (Chapter 2, page 63). As you know, neutralization of an acid with a base is also a type of double replacement reaction. For example,

$$\underset{\text{acid}}{HCl(aq)} + \underset{\text{base}}{NaOH(aq)} \rightarrow \underset{\text{salt}}{NaCl(aq)} + \underset{\text{water}}{H_2O(l)}$$

According to the modified Arrhenius theory, acids produce hydronium ions in solution and bases produce hydroxide ions in solution. If we mix a solution of an acid with a solution of a base, we must be mixing solutions of hydronium and hydroxide ions. Therefore, when an acid neutralizes a base, the modified Arrhenius theory predicts

$$H_3O^+(aq) + OH^-(aq) \rightarrow 2\,H_2O(l)$$

Neutralization can now be defined as the reaction between hydronium and hydroxide ions to produce water.

DID YOU KNOW?

Nonmetal Oxides in Water

Another interpretation for the production of an acidic solution by a nonmetal oxide is to consider a two-step reaction with water. For example,

$$CO_2(g) + H_2O(l) \rightarrow H_2CO_3(aq)$$
$$H_2CO_3(aq) + H_2O(l) \rightarrow H_3O^+(aq) + HCO_3^-(aq)$$

The solution in Communication Example 2 is the sum of these two steps.

EXTENSION

Soil Acidity and Plant Growth

A fairly neutral soil pH is important for plant growth. At lower pH, metal ions can be released from the soil minerals. These ions can damage growing plants. Why is some soil acidic, and what can be done to reduce the ill effects? This audio clip tells you more.

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Acid Deposition

What exactly is acid deposition, or the more common term, acid rain? Like so many other issues related to science and technology, there are many perspectives and many technological solutions with various consequences. Here is a brief outline of different perspectives to help you organize your knowledge of acid deposition.

A Scientific Perspective

Normal precipitation, without any pollutants from human activity or catastrophic natural events like volcanic eruptions, is slightly acidic, having a pH of 5.6 or above. The acidity is the result of natural carbon dioxide dissolving in atmospheric moisture to form carbonic acid. Nitrogen oxides from lightning strikes and plant decay are other natural sources of acids in rain and other forms of precipitation.

Acid deposition is caused by nonmetal oxides. The formula NO_x represents several oxides of nitrogen, including $N_2O(g)$, $NO_2(g)$, and $N_2O_4(g)$. Likewise, SO_x represents sulfur oxides including $SO_2(g)$ and $SO_3(g)$, and CO_x represents gases such as $CO_2(g)$ and $CO(g)$.

Acid deposition includes any form of acid precipitation (rain, snow, or hail) and condensation from acid fog, as well as acid dust from dry air. A pH of less than 5.6 in the water from acid deposition is usually considered to be a potential problem. Empirical work indicates that the main causes of acid deposition in North America are sulfur dioxide and various nitrogen oxides, NO_x. These compounds react with water in the atmosphere to produce various acids. Oxides of sulfur and nitrogen are combustion products from sources such as automobiles, coal-burning power plants, and smelters. According to Statistics Canada, sulfur dioxide emissions have been declining across Canada, but nitrogen oxide emissions have remained relatively unchanged in the last decade.

An Ecological Perspective

Scientific research has repeatedly shown that acid deposition has increased the acidity of some lakes and streams to the point where aquatic life is depleted and waterfowl populations are threatened. Hundreds of lakes in Eastern Canada are now devoid of aquatic plant and animal life due to the lakes' high acidity from acid deposition. Some organisms are more susceptible than others to changes in acidity, but, eventually, the increased acidity (lower pH) leads to the "death" of a lake. Acid deposition has also been linked to forest decline in Eastern Canada and other parts of the world, but there is some dispute as to whether the major cause of the problem is particulates or acid precipitation (**Figure 2**).

If we see ourselves as an integral part of the environment, we may view environmental problems a little differently. These considerations are a feature of the Aboriginal worldview.

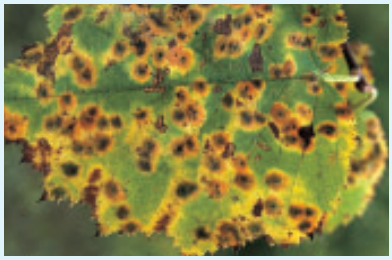

Figure 2
The effect of acid deposition on deciduous trees

An Economic Perspective

The environmental problems described above create economic problems. Acid deposition is endangering the fishing, tourism, agriculture, and forestry industries. Use of alternative energy sources or implementation of pollution-reducing technologies means spending money that consumers and industries may feel they cannot afford. If an industry shuts down, people lose jobs, and the cost of social assistance escalates. From the same perspective, future costs of doing nothing are likely to be staggering.

A Political Perspective

Political pressures and opinions have resulted in legislation limiting the production of sulfur oxides and nitrogen oxides. Some people argue that there should be even stiffer legislation to regulate industries and vehicle emissions, but others argue that there should be less government interference and voluntary industry compliance.

A Technological Perspective on Reducing Acid Deposition

Technologies are now available for the development and use of alternative fuels, the removal of sulfur from fossil fuels, and the recovery of oxides from exhaust gases.

Case Study Questions

Set up a research group to study technologies for reducing the sources of acid deposition.

In your group:

1. Prepare a list of possible technologies.
2. Assign one specific technological solution to each member or smaller sub-group. Using the library and the Internet, collect information about each technological solution, including its purpose, materials, processes, intended results, any information about how well it works, and any unintended consequences.

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3. Compare the technologies. Are some technologies better than others? Why?
4. Assemble and communicate the information as directed by your teacher.

SUMMARY The Modified Arrhenius Theoretical Definitions

- Acids are substances that react with water to produce hydronium ions.
- Most bases are substances that react with water to produce hydroxide ions.
- Neutralization can be explained as the reaction between hydronium ions and hydroxide ions to produce water.

Section 6.4 Questions

1. Identify two differences between the original Arrhenius definition of an acid and the modified Arrhenius definition.

2. Compare the original Arrhenius definition of a base with the modified Arrhenius definition. What is the same and what is different?

3. Evaluate the modified Arrhenius theory in terms of its ability to explain the results of Investigation 6.2.
(a) Where possible, write a valid chemical equation to explain the evidence you collected.
(b) Which substances can the modified Arrhenius theory not explain? Identify some questions that you would need to have answered in order to explain the evidence for these substances.
(c) You know that Arrhenius' original theory did not work very well. In your opinion, does the modified Arrhenius theory get a "passing grade"? Why?

4. Test the explanatory power of the modified Arrhenius definitions by explaining the following evidence. For each of the following compounds, write a dissociation equation where appropriate, and then write a chemical equation showing reactions with water to produce either hydronium or hydroxide ions (consistent with the evidence):
(a) HBr(g) in solution shows a pH of 2 on pH paper.
(b) $Na_3PO_4(s)$ forms a solution with a pH of 8.
(c) $NaHSO_3(s)$ in solution turns blue litmus red.
(d) $Na_2HPO_4(s)$ in solution turns red litmus blue.
(e) $Na_2O(s)$ in solution turns red litmus blue.
(f) $SO_3(g)$ in solution turns blue litmus red.
(g) KOH(s) yields a solution with a pH of 12.

5. According to the modified Arrhenius theory, what is the balanced chemical equation for the reaction of aqueous nitric acid and aqueous potassium hydroxide?

6. Describe how the modified Arrhenius theory simplifies the many different examples that you have previously seen of the neutralization of an acid with a base.

7. What test do you put a theory through after testing its explanatory power?

8. Technological problems often have multiple solutions that involve different products and processes. All technological solutions or "fixes" have consequences. A decision to use one approach or another involves looking at the risks and benefits of each.

Suppose a tanker truck, carrying a concentrated solution of sodium hydroxide destined for a pulp and paper company, crashes on the highway. Should this dangerous spill of a base be neutralized or diluted? Provide a brief list of pro and con arguments for each proposed solution.

Extension

9. Compare the animal skin tanning process traditionally used by Aboriginal peoples and a current process that uses synthetic chemicals. Outline the use of acids and bases in both processes. Evaluate the two technologies in terms of quality of the product and environmental impacts.

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6.5 The Strength of Acids and Bases

DID YOU KNOW ?

The Origin of "Acid"

The word "acid" comes from the Latin term "*acere*," which means "to make sour." A sour taste was likely associated with citrus fruits (citric acid) and sour wine (acetic acid).

Acids and bases can be distinguished by means of a variety of properties (**Table 1**). Some properties of acids and bases are more useful than others to a chemist, especially those that can be used as diagnostic tests, such as the litmus or pH tests.

Table 1 Empirical Properties of Acids and Bases in Aqueous Solution

Acids	Bases
taste sour*	taste bitter and feel slippery*
turn blue litmus red	turn red litmus blue
have pH less than 7	have pH greater than 7
neutralize bases	neutralize acids
react with active metals to produce hydrogen gas	
react with carbonates to produce carbon dioxide	

*For reasons of safety, it is not appropriate to use taste or touch as diagnostic tests in the laboratory.

Acids are common substances. They occur naturally in many plants and animals. Technological products and processes employ acids in a wide variety of situations, from commonplace consumer products like cleaners, to large industrial processes like the fertilizer industry. Do all acids have the same properties and to the same degree?

INVESTIGATION 6.3 *Introduction*

Comparing the Properties of Acids (Demonstration)

Complete the Design by specifying the controlled variables. In the Evaluation, suggest several improvements to the Design.

Purpose

The purpose of this demonstration is to create the concept of strengths of acids.

Problem

How do the properties of two common acids compare?

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	○ Materials	● Evaluation (1, 3)
○ Hypothesis	○ Procedure	
○ Prediction	● Evidence	

Design

The properties of aqueous solutions of two acids, hydrochloric acid and acetic acid, are observed and compared. Diagnostic tests include the litmus test, conductivity test, and reaction with an active metal. Two important controlled variables are …

To perform this investigation, turn to page 261.

Strong and Weak Acids

The evidence from Investigation 6.3 clearly shows that acids with the same initial concentration can have different degrees of acidic properties. The difference in degree of acidity was shown by the conductivity measurements and the differences in the rates of reaction. Controlling variables is very important when comparing properties such as conductivity and pH. For example, a very dilute solution of a strong acid could have a higher pH (lower hydronium ion concentration) than a more concentrated solution of a weak acid. Therefore, when comparing acid strengths, it is important that the concentration and temperature of the acids be controlled.

In terms of its empirical properties, an acid is described as a *weak acid* if its characteristic properties under the same conditions are less than those of a common strong acid, such as hydrochloric acid. There are relatively few strong acids; hydrochloric, sulfuric, and nitric acids are the most common strong acids. Most common acids are weak acids. The concept of strong and weak acids was developed to describe and explain the differences in properties of acids.

You can explain the differences in properties between strong and weak acids using the modified Arrhenius theory and the extent of reaction with water. For example, hydrochloric acid is a strong acid with a high conductivity, a high rate of reaction with active metals and carbonates, and a relatively low pH. These empirical properties suggest that there are many ions present in the solution and, specifically, a high concentration of hydronium ions. This evidence would be consistent with the idea that a **strong acid** reacts completely (more than 99%) with water to form hydronium ions. The high concentration of $H_3O^+(aq)$ ions gives the solution strong acid properties and a low pH.

$$HCl(aq) + H_2O(l) \xrightarrow{>99\%} H_3O^+(aq) + Cl^-(aq)$$

According to this chemical equation for the reaction of hydrochloric acid with water, for each mole of hydrochloric acid that reacts with water, about one mole of hydronium ions is produced.

A weak acid is an acid that has a relatively low conductivity, a lower rate of reaction with active metals and carbonates, and a relatively high pH compared with strong acids. This evidence suggests the presence of fewer hydronium ions in the acidic solution. Based on this evidence, a **weak acid** reacts incompletely with water to form relatively few hydronium ions. Measurements of pH indicate that most weak acids react much less than 50%. Acetic acid, a common weak acid, is a typical example. The relatively low concentration of hydronium ions gives the solution weaker acid properties and a pH closer to 7:

$$CH_3COOH(aq) + H_2O(l) \xrightarrow{<50\%} H_3O^+(aq) + CH_3COO^-(aq)$$

Under the same conditions, weak acids have fewer hydronium ions and are, therefore, less acidic. For this and other reasons, weak acids are generally much safer to handle than strong acids. You can even eat and drink many of them (**Figure 2**)! Lactic acid is found in dairy products, butanoic acid is found in rancid butter, citric acid is found in citrus fruits, oxalic acid is found in rhubarb, and long-chain fatty acids, such as stearic acid, are found in animal fats. Most of the acids you are likely to encounter are classed as weak acids.

Practice

1. State two diagnostic tests that can be used to distinguish between strong and weak acids. Word each test in the format, "*If* [procedure], *and* [evidence], *then* [analysis]." (See Appendix C.4.)
2. What is the key idea used to explain the difference between strong and weak acids?
3. State three common examples of strong acids.
4. A laboratory solution of hydrochloric acid has a concentration of 0.15 mol/L.
   (a) Calculate the concentration of hydronium ions in this solution.
   (b) Calculate the pH of this solution.
5. A laboratory solution of acetic acid has a concentration of 0.15 mol/L. Will the pH of this solution be lower or higher than the pH of the hydrochloric acid solution in the previous question? Briefly explain your answer.

DID YOU KNOW ?

Aboriginal "Herbal Aspirin"—A Weak Acid

Aboriginal peoples of North America have a rich history of herbal medicine. In fact, most of the top 10 herbs used medically today were first used by Aboriginal peoples. Herbal medicine is part of their traditional knowledge—empirical knowledge developed over thousands of years. For example, Aboriginal peoples traditionally used the white willow (**Figure 1**) to obtain a substance that relieves pain and lowers fevers.

From a Western science perspective, this substance is called salicin. Salicin is converted to salicylic acid (closely related to acetylsalicylic acid, known as Aspirin) in the body. Salicylic acid is a weak acid from the same family of acids as the simpler acetic acid.

Figure 1
A white willow

Figure 2
Many naturally occurring acids are weak acids.

Figure 3
Ammonia gas is released from smelling salts such as ammonium carbonate. Ammonia irritates the nasal passages and stimulates a sharp intake of breath, rousing someone who feels faint or has fainted.

Strong and Weak Bases

Evidence indicates that there are both strong bases (such as sodium hydroxide) and weak bases (such as ammonia). For equal concentrations of solutions, strong bases have high electrical conductivity and very high pH (>>7); whereas weak bases have low electrical conductivity and pH closer to (but greater than) 7. We can explain the behaviour of strong bases as a dissociation in an aqueous solution to increase the hydroxide ion concentration. For example, if you dissolve some solid lye (sodium hydroxide) to make a solution for cleaning a drain, the sodium hydroxide dissociates completely as it dissolves.

$$NaOH(s) \rightarrow Na^+(aq) + OH^-(aq)$$

From this equation, for every one mole of sodium hydroxide that dissolves, one mole of hydroxide ion is produced in the solution. This mole ratio explains why bases like sodium hydroxide have such strong basic properties. Further evidence indicates that all soluble ionic hydroxides are **strong bases**: 100% of dissolved ionic hydroxides dissociate to release hydroxide ions. In general,

$$MOH(aq) \rightarrow M^+(aq) + OH^-(aq)$$

where M represents a metal ion.

What about weak bases? How can we explain their properties? The pure compounds (such as ammonia gas, $NH_3(g)$, **Figure 3**) do not contain hydroxide ions, so they cannot dissociate to release hydroxide ions. Nevertheless, pH measurements above 7 indicate that solutions of weak bases contain hydroxide ions in a higher concentration than in pure water. The explanation is found in the modified Arrhenius theory: **a weak base** reacts partially (usually much less than 50%) with water to produce relatively few hydroxide ions compared with a similar amount of a strong base, which accounts for the weaker basic properties of weak bases. Most bases, other than soluble ionic hydroxides, are weak bases. Weak bases may be either ionic or molecular compounds in their pure state. In general,

$$B(aq) + H_2O(l) \xrightarrow{<50\%} OH^-(aq) + \text{balancing entity}$$

where B represents a base (molecule or ion).

SAMPLE problem 6.4

Explain the evidence that an ammonia solution (window cleaner) is a basic aqueous solution, as demonstrated by a litmus paper test (Investigation 6.2).

According to the modified Arrhenius theory, ammonia reacts with water to produce hydroxide ions, which explains the evidence that the solution is basic:

$$NH_3(aq) + H_2O(l) \rightarrow OH^-(aq) + ?$$

Determine the second product by balancing the atoms and charge in the chemical reaction equation.

Using the generalization that only soluble ionic hydroxides are strong bases, ammonia must be a weak base. According to the modified Arrhenius theory, this means less than 50% reaction with water.

The final chemical equation for the reaction of ammonia with water illustrates the theory to explain the evidence:

$$NH_3(aq) + H_2O(l) \xrightarrow{<50\%} OH^-(aq) + NH_4^+(aq)$$

The presence of hydroxide ions explains why the solution is basic, and the less-than-complete reaction explains the weak base properties. (Note that both atoms and charge are conserved in the balanced equation.)

EXTENSION

Strong/Weak and Concentrated/Dilute

"Concentrated" and "dilute" are terms used to describe solutions qualitatively. Learn more about the distinction between these terms and "strong" and "weak."

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SAMPLE problem 6.5

Explain the weak base properties of baking soda.

Sodium hydrogen carbonate (baking soda, **Figure 4**) is an ionic compound with high solubility that dissociates in water to produce aqueous ions of sodium and hydrogen carbonate:

$$NaHCO_3(s) \rightarrow Na^+(aq) + HCO_3^-(aq)$$

The sodium ion cannot be responsible for the basic properties of the solution, because many sodium compounds (such as NaCl(aq)) form neutral solutions. The basic character of hydrogen carbonate ion solutions can be explained as resulting from their reaction with water:

$$HCO_3^-(aq) + H_2O(l) \xrightarrow{<50\%} OH^-(aq) + H_2CO_3(aq)$$

The presence of hydroxide ions explains the basic properties of sodium hydrogen carbonate, and the incomplete reaction explains the weak base properties.

COMMUNICATION example

Solid sodium acetate is dissolved in water. The final solution is tested and found to have a pH of about 8. Explain this evidence by writing balanced chemical equations.

Solution

$$NaCH_3COO(s) \rightarrow Na^+(aq) + CH_3COO^-(aq)$$

$$CH_3COO^-(aq) + H_2O(l) \xrightarrow{<50\%} OH^-(aq) + CH_3COOH(aq)$$

Figure 4
Baking soda is a common household chemical, but it requires an uncommonly sophisticated theory to explain or predict its properties.

We now have explanations for the production of hydroxide ions by bases: Strong bases (commonly ionic hydroxides) dissociate completely in solution to produce hydroxide ions; and weak bases partially react with water to increase the hydroxide ion concentration of the solution (modified Arrhenius theory).

Practice

6. Suppose you had two aqueous solutions with the same solute concentration, one containing a strong base and the other a weak base. Describe several ways to distinguish between these two solutions using diagnostic tests.

7. How would strong and weak bases be distinguished using pOH values? What variables would need to be controlled?

8. Describe how you can distinguish a strong base from a weak base using
(a) the formula of the solute in the solution
(b) the modified Arrhenius theory

9. Write balanced chemical equations to show all changes that occur when solid sodium sulfate dissolves in water to produce a solution that turns red litmus paper blue.

Figure 5
A common ingredient in a solution used to remove rust is phosphoric acid, which surprisingly is also a common ingredient in cola soft drinks.

Polyprotic Substances

Some acids have only one acidic hydrogen atom in their compound formula (HA) and can react only once with water to produce hydronium ions. These acids are called **monoprotic acids**. Most strong acids, such as HCl(aq), as well as many weak acids, such as HCN(aq), are monoprotic. There are, however, some acids that contain more than one acidic hydrogen in their compound formulas (H_xA) and can react more than once with water. These acids are called **polyprotic acids**. For example, phosphoric acid, $H_3PO_4(aq)$, found in cola soft drinks (**Figure 5**) and rust removers, initially reacts with water to produce hydronium ions:

$$H_3PO_4(aq) + H_2O(l) \overset{<50\%}{\rightarrow} H_3O^+(aq) + H_2PO_4^-(aq)$$

This reaction is less than 50% complete; therefore, phosphoric acid is a weak acid. The dihydrogen phosphate ion, a product of this first reaction with water, can react with an additional water molecule to produce more hydronium ions, but this reaction is even less complete (<1%):

$$H_2PO_4^-(aq) + H_2O(l) \overset{<1\%}{\rightarrow} H_3O^+(aq) + HPO_4^{2-}(aq)$$

Similarly, the hydrogen phosphate ion produced in this second reaction with water can in principle react again, but this reaction does not occur to any appreciable extent:

$$HPO_4^{2-}(aq) + H_2O(l) \overset{\sim 0\%}{\rightarrow} H_3O^+(aq) + PO_4^{3-}(aq)$$

With all of these possible reactions, you might think that phosphoric acid solutions would be very acidic, but only the first reaction is significant. Phosphoric acid is a weak acid: The pH of its solution is noticeably higher than the pH of a strong acid at the same concentration. Based on pH and other evidence, the first reaction is already incomplete and the subsequent reactions become even less complete. ***In general, polyprotic acids are weak acids whose reaction with water decreases with each successive step.***

Acid	Concentration	pH
HCl(aq)	0.1 mol/L	1.0
$H_3PO_4(aq)$	0.1 mol/L	1.7

An important exception to the rule that polyprotic acids are weak acids is sulfuric acid. It is a strong acid because the first reaction with water is essentially complete. The second reaction, however, is much less than 50% complete.

The same concepts also apply to weak bases. Some bases, like $CH_3COO^-(aq)$, are **monoprotic bases**, meaning they can react with water only once to produce hydroxide ions. Other bases, like $CO_3^{2-}(aq)$, are **polyprotic bases** because they can react more than once with water, but all reactions with water are much less than 50%:

$$CO_3^{2-}(aq) + H_2O(l) \overset{<50\%}{\rightarrow} OH^-(aq) + HCO_3^-(aq)$$

$$HCO_3^-(aq) + H_2O(l) \overset{<1\%}{\rightarrow} OH^-(aq) + H_2CO_3(aq)$$

Evidence shows that a carbonate ion solution is less basic than a strong base at the same concentration. ***In general, polyprotic bases are weak bases whose reaction with water decreases with each successive step.***

Base	Concentration	pH
NaOH(aq)	0.1 mol/L	13.0
$Na_2CO_3(aq)$	0.1 mol/L	11.4

Polyprotic substances are generally weak acids and weak bases that undergo multiple reactions with water to produce hydronium ions and hydroxide ions, respectively. In all cases, the successive reactions with water are increasingly incomplete.

Learning Tip

Monoprotic bases are sometimes called monobasic bases; polyprotic bases are sometimes called polybasic bases, which could mean dibasic, tribasic, etc. This nomenclature is often used on consumer or commercial products.

Learning Tip

A base like barium hydroxide, $Ba(OH)_2(aq)$, is not a polyprotic base because there is no possibility of successive reactions with water. Barium hydroxide dissociates to produce hydroxide ions. It does not matter that there are two moles of hydroxide ions produced in the dissociation of one mole of barium hydroxide. When barium hydroxide reacts with a strong acid, there is only one reaction that can take place: between hydroxide and hydronium ions.

SUMMARY Strong and Weak Acids and Bases

Table 2 Strong and Weak Acids and Bases in Aqueous Solution

	Strong acids	Weak acids	Strong bases	Weak bases
empirical properties (same *c* and *t*)	very low pH ($<< 7$)	medium to low pH (<7)	very high pH ($>> 7$)	medium to high pH (>7)
	high conductivity	low conductivity	high conductivity	low conductivity*
	fast reaction rate	slow reaction rate	fast reaction rate	slow reaction rate
modified Arrhenius theory	completely react with water to form $H_3O^+(aq)$	partially react with water to form $H_3O^+(aq)$	completely dissociate to form $OH^-(aq)$	partially react with water to form $OH^-(aq)$

* applies only to weak bases that are molecular

Section 6.5 Questions

1. List three common examples of a strong acid and one common example of a strong base.
2. In a sentence, summarize the empirical evidence for strong and weak acids and bases.
3. According to the modified Arrhenius theory, explain the difference between
   (a) strong and weak acids (b) strong and weak bases
4. Acids and bases can be concentrated or dilute, and strong or weak. Illustrate the meaning of these terms by sketching a diagram for each of the following solutions. Use simple symbols to represent molecules and ions, and dots to represent water molecules.
   (a) a concentrated strong acid
   (b) a dilute strong acid
   (c) a concentrated weak acid
   (d) a dilute weak acid
5. The pH values of two acids with the same concentration and temperature are 2 and 6. Which is likely the strong acid and which is likely the weak acid? Justify your answer.
6. Solid sodium fluoride dissolves in water to produce a solution with a pH of 8. Write chemical equations to show the changes that have occurred.
7. Define the term "polyprotic." State some examples of polyprotic acids and bases.
8. How does the completeness of the reaction change in successive reactions of a polyprotic substance with water?
9. Write at least three diagnostic tests to determine which of two unlabelled solutions is acetic acid or hydrochloric acid. Word each test in the format, "*If* [procedure], *and* [evidence], *then* [analysis]." (See Appendix C.4.)
10. Describe the precautions that should be taken for safe handling and disposal of acids and bases.
11. Write the Design (including variables) and the complete Analysis of the report for the following investigation:

    Purpose

    The purpose of this investigation is to compare the strengths of several acids.

    Problem

    What is the order of several common acids in terms of decreasing strength?

    Evidence

    Table 3 Acidity of 0.10 mol/L Acids

Acid solution	Formula	pH
hydrochloric acid	HCl(aq)	1.00
acetic (ethanoic) acid	$CH_3COOH(aq)$	2.89
hydrofluoric acid	HF(aq)	2.11
nitric acid	$HNO_3(aq)$	1.00
hydrocyanic acid	HCN(aq)	5.15

12. Identify the strong acids in **Table 3**. Justify your answer with appropriate chemical equations and calculations.
13. Many products found in our homes contain acids and bases. Find examples of these products and make a list of the acids and bases they contain. Where possible, identify the acids and bases as either strong or weak.

Extension

14. Many cleaning products are often available in concentrated or dilute form. They may also contain different types of acids or bases. Using this general example, describe the importance of understanding the terms "strength" and "concentration." Include at least two perspectives.

INVESTIGATION 6.1

Properties of Acids and Bases

In this investigation, you will use your previous knowledge of properties of substances, and practise your problem-solving skills. You are provided with solutions of approximately equal concentrations, at the same temperature, of the following pure substances: $CaCl_2(s)$, $C_3H_4OH(COOH)_3(s)$, $C_6H_{12}O_6(s)$, $Ca(OH)_2(s)$, $NH_3(g)$, $NaHSO_4(s)$, $CH_3OH(l)$, $H_2SO_4(l)$, $Na_2CO_3(s)$. Remember to include variables in your Design, and safety and disposal instructions in your Procedure.

Solutions may be toxic, irritant, or corrosive; avoid eye and skin contact.

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	● Materials	● Evaluation (1, 2, 3)
○ Hypothesis	● Procedure	
● Prediction	● Evidence	

Purpose

The purpose of this investigation is to test previous knowledge about the properties of acids and bases.

Problem

What properties are most useful for distinguishing acids and bases from other classes of compounds?

INVESTIGATION 6.2

Testing Arrhenius' Acid–Base Definitions

In this investigation, you will use Arrhenius' acid–base theory to make predictions, test these predictions using diagnostic tests, and finally, evaluate Arrhenius' theory. For simplicity, assume that Arrhenius' theory restricts dissociation and ionization to only two ions. In your Design, be sure to identify all variables, including any controls.

Purpose

The purpose of this investigation is to test Arrhenius' definitions of an acid and a base.

Problem

Which of the substances tested may be classified as an acid, a base, or neutral, using Arrhenius' definitions?

Materials

lab apron
eye protection
conductivity apparatus
blue litmus paper
red litmus paper
any other materials necessary for diagnostic tests

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	○ Materials	● Evaluation (1, 2, 3)
○ Hypothesis	● Procedure	
● Prediction	● Evidence	

aqueous 0.10 mol/L solutions of:
- hydrogen chloride (a gas in solution)
- acetic acid (vinegar)
- sodium hydroxide (lye, caustic soda)
- calcium hydroxide (slaked lime)
- ammonia (cleaning agent)
- sodium carbonate (washing soda, soda ash)
- sodium hydrogen carbonate (baking soda)
- sodium hydrogen sulfate (toilet bowl cleaner)
- calcium oxide (lime)
- carbon dioxide (carbonated beverages)
- aluminium nitrate (salt solution)
- sodium nitrate (fertilizer)

Solutions may be toxic, irritant, or corrosive; avoid eye and skin contact.

INVESTIGATION 6.3

Comparing the Properties of Acids (Demonstration)

Complete the Design by specifying the controlled variables. In the Evaluation, suggest several improvements to the Design.

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	○ Materials	● Evaluation (1, 3)
○ Hypothesis	○ Procedure	
○ Prediction	● Evidence	

Solutions may be corrosive; avoid eye and skin contact.

Purpose

The purpose of this demonstration is to create the concept of strengths of acids.

Problem

How do the properties of two common acids compare?

Design

The properties of aqueous solutions of two acids, hydrochloric acid and acetic acid, are observed and compared. Diagnostic tests include the litmus test, conductivity test, and reaction with an active metal. Two important controlled variables are …

Materials

lab apron
eye protection
2 150 mL beakers
2 petri dishes
conductivity apparatus or probe
steel wool
scissors
overhead projector
red and blue litmus paper
magnesium ribbon (about 5 cm)
100 mL of 1.0 mol/L HCl(aq)
100 mL of 1.0 mol/L $CH_3COOH(aq)$
distilled water bottle
baking soda

Procedure

1. Pour equal volumes of each acid into separate, clean beakers.
2. Dip a piece of red and a piece of blue litmus paper into each acid and record colour changes.
3. Rinse the conductivity probe with distilled water and insert into one acid. Record evidence of conductivity.
4. Repeat step 3 for the other acid.
5. Place two clean petri dishes on the stage of the overhead projector.
6. Carefully fill each dish about half full with each acid.
7. Clean a strip of magnesium ribbon with steel wool and cut into two equal lengths (about 2 cm each).
8. Add a piece of magnesium simultaneously to each petri dish.
9. Note and record evidence of the rate of reaction.
10. Neutralize the acids with sodium hydrogen carbonate (baking soda) and dispose of solutions into the sink with lots of running water.

Chapter 6 SUMMARY

Outcomes

Knowledge

- recall the empirical definitions of acidic, basic, and neutral solutions determined by using indicators, pH, and electrical conductivity (6.1)
- calculate $H_3O^+(aq)$ and $OH^-(aq)$ concentrations, pH, and pOH of acid and base solutions based on logarithmic expressions (6.2)
- use appropriate SI units to communicate the concentration of solutions and express pH and concentration to the correct number of significant digits (6.2)
- compare magnitude changes in pH and pOH with changes in concentration for acids and bases (6.2)
- explain how the use of indicators, pH meters, or pH paper can be used to measure $[H_3O^+(aq)]$ (6.3)
- use the modified Arrhenius theory to define acids as substances that produce $H_3O^+(aq)$ in aqueous solutions and bases as substances that produce $OH^-(aq)$ in aqueous solutions and recognize that the definitions are limited (6.4)
- define neutralization as a reaction between hydronium and hydroxide ions (6.4)
- differentiate between strong acids and bases and weak acids and bases, qualitatively, using the modified Arrhenius (reaction with water) theory and dissociation (6.5)
- compare the reaction with water (ionization) of monoprotic with that of polyprotic acids and bases (6.5)

STS

- state that the goal of technology is to provide solutions to practical problems (all sections)
- recognize that solutions to technological problems may have both intended and unintended consequences (all sections)

Skills

- initiating and planning: design a procedure to determine the properties of acids and bases (6.1, 6.5); design an experiment to differentiate between weak and strong acids, and between weak and strong bases (6.1, 6.3, 6.4); describe procedures for safe handling, storing, and disposal of materials (6.1, 6.3, 6.4, 6.5)
- performing and recording: construct and analyze a table or graph comparing pH and hydronium ion concentration (6.2)
- analyzing and interpreting: use a pH meter (or paper) and indicators to determine acidity and pH (6.1, 6.3, 6.4, 6.5)
- communication and teamwork: work collaboratively to assess technologies (6.4)

Key Terms

6.1
hydronium ion

6.2
pH
pOH

6.3
acid–base indicator

6.4
acid (modified Arrhenius)
base (modified Arrhenius)
neutralization

6.5
strong acid
weak acid
strong base
weak base
monoprotic acid
polyprotic acid
monoprotic base
polyprotic base

Key Equations

$$pH = -\log[H_3O^+(aq)] \qquad [H_3O^+(aq)] = 10^{-pH} \qquad (6.2)$$

$$pOH = -\log[OH^-(aq)] \qquad [OH^-(aq)] = 10^{-pOH} \qquad (6.2)$$

MAKE a summary

1. Create a concept map starting with "Acids and Bases" in the centre of a page. Include empirical and theoretical classification, all of the key terms and equations, as well as any other information you think may be useful in studying for a test on this chapter.
2. Refer back to your answers to the Starting Points questions at the beginning of this chapter. How has your thinking changed?

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The following components are available on the Nelson Web site. Follow the links for *Nelson Chemistry Alberta 20–30*.

- an interactive Self Quiz for Chapter 6
- additional Diploma Exam-style Review questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in this chapter.

Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix H. Exam study tips and test-taking suggestions are on the Nelson Web site. Science Directing Words used in Diploma Exams are in bold type.

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Part 1

1. Which set of properties best describes an acidic solution?

	conductivity	litmus	pH
A.	yes	blue	8
B.	yes	red	4
C.	no	red	5
D.	no	blue	7

2. What is the modern replacement for the original concept of a hydrogen ion in an acidic solution?

A. $H^+(aq)$
B. $H_2^+(aq)$
C. $H_2O^+(aq)$
D. $H_3O^+(aq)$

3. NR A window cleaning solution has a hydroxide ion concentration of 2.4×10^{-4} mol/L.
The pOH of this solution is _____.

4. An acidic fruit juice has a hydronium ion concentration of 1.45×10^{-4} mol/L. The correctly reported pH is

A. 3.8
B. 3.84
C. 3.839
D. 3.8386

5. In a chemical analysis the hydronium ion concentration of a solution can be determined by all of the following *except*

A. pH paper
B. a pH meter
C. indicators
D. conductivity apparatus

6. NR A solution with a pH of 11.83 has a hydronium ion concentration of $\boldsymbol{a.b} \times 10^{-\boldsymbol{cd}}$ mol/L. The values of ***a***, ***b***, ***c***, and ***d*** are __ __ __ __.

7. If a water sample test shows a pH of 5, by what factor would the hydronium ion concentration have to increase or decrease to completely neutralize the sample?

A. increase by a factor of 2
B. decrease by a factor 2
C. increase by a factor of 100
D. decrease by a factor of 100

Use the following information to answer questions 8 and 9.

As part of a chemical analysis, an unknown solution was tested and found to have a pH of 6.8.

8. NR What is the colour, in order, of the following indicators in this solution?
methyl red
chlorophenol red
bromothymol blue
methyl orange

Using the colour codes: 1 = green, 2 = red, 3 = yellow, 4 = other colour, the list of numbered colour codes, in order of indicators, is ___ ___ ___ ___.

9. The hydronium ion concentration in this solution is

A. 2×10^{-7} mol/L
B. 8×10^{-6} mol/L
C. 6.3×10^{6} mol/L
D. 1.58×10^{-7} mol/L

10. The theoretical property that all strong acids have in common is that they all

A. form very concentrated solutions
B. react partially with water to form hydronium ions
C. react completely with water to form hydronium ions
D. are polyprotic acids forming multiple hydronium ions

11. NR Solutions of four different acids with the same concentration at the same temperature have the following characteristics:
Acid 1 pH = 4
Acid 2 pH = 1
Acid 3 $[H_3O^+_{(aq)}] = 10^{-3}$ mol/L
Acid 4 $[H_3O^+_{(aq)}] = 10^{-6}$ mol/L

When the acids are arranged, in order, from strongest acid to weakest acid, the order is ___ ___ ___ ___. (Record all four digits.)

Part 2

12. Complete the Analysis and Evaluation (design only) for the following investigation:

Problem

Which of the chemicals, numbered 1 to 7, is $KCl_{(s)}$, $Ba(OH)_{2(s)}$, $Zn_{(s)}$, $C_6H_5COOH_{(s)}$, $Ca_3(PO_4)_{2(s)}$, $C_{25}H_{52(s)}$ (paraffin wax), and $C_{12}H_{22}O_{11(s)}$?

Design

Equal amounts of each chemical are added to equal volumes of water. The mixtures are tested for their conductivity and effect on litmus paper.

Evidence

Table 1 States of Matter of Elements

Chemical	Solubility in water	Conductivity of solution	Litmus paper test
1	high	none	no change
2	high	high	no change
3	none	none	no change
4	high	high	red to blue
5	none	none	no change
6	none	none	no change
7	low	low	blue to red

13. If you are given a measurement of the pH of a solution, what determines the certainty (number of significant digits) of the calculated hydronium ion concentration?

14. **Determine** the hydronium ion concentration in each of the following solutions.
(a) cleaning solution with pH = 11.562
(b) fruit juice with pH = 3.5

15. One sample of rainwater has a pH of 5, while another sample has a pH of 6. **Compare** the hydronium ion concentrations in the two samples.

16. Can a pOH equal zero? **Justify** your answer mathematically.

17. Separate samples of an unknown solution turned both methyl orange and bromothymol blue indicators to yellow, and turned bromocresol green indicator to blue.
(a) Estimate the pH of the unknown solution.
(b) **Determine** its approximate hydronium ion concentration.

18. Acids and bases may be either strong or weak.
DE (a) **Design** an experiment to distinguish between strong and weak acids, and strong and weak bases. Include appropriate diagnostic tests and controlled variables.
(b) Use the modified Arrhenius theory to **explain** how strong and weak acids differ, and how strong and weak bases differ.

19. Write appropriate chemical equations to **explain** the acidic or basic properties of each of the following substances when added to water:
(a) sodium sulfide (basic)
(b) hydrogen bromide (acidic)
(c) potassium hydroxide (basic)
(d) benzoic acid, $C_6H_5COOH_{(aq)}$ (acidic)

20. There are many factors that determine the effectiveness of a cleaner. Considering that most food is acidic and most cleaners are basic, what is the type of possible chemical reaction? **Illustrate** your answer with a chemical equation.

21. Citrus fruits such as oranges, lemons and grapefruit contain
DE citric acid, $H_3C_6H_5O_7(aq)$ which is a weak polyprotic acid.
(a) **Why** is citric acid called a polyprotic acid?
(b) Write chemical equations for all possible reactions when pure citric acid dissolves in water.
(c) In general, state how the reaction with water changes with each successive step.

22. Determining the acidity of a solution is an important task in many applications such as scientific research, industrial processes, and environmental studies. What technologies are available to determine the acidity of a solution? Use at least three different criteria to **compare** the technologies you identified.

Extension

23. Many chemicals that are potentially toxic or harmful to the environment have maximum permissible concentration levels set by government legislation.
(a) If the chemical is dangerous, should the limit be zero?
(b) Is a zero level theoretically possible?
(c) Is a zero level empirically measurable?
(d) If a non-zero limit is set, what groups should have input into this decision and how do you think this limit should be determined?

24. What is acid deposition? Your report should include
- the names of the acids that are typically present
- whether the acids are strong or weak
- whether it is possible to predict which acids have a greater effect in the environment, with reasons

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Part 1

1. A solution such as tap water is a
- A. pure substance
- B. compound
- C. homogeneous mixture
- D. heterogeneous mixture

Use this information to answer questions 2 and 3.

Iodine dissolved in alcohol is used as an external medication for its disinfecting and antibacterial properties. To study these effects, 4.52 g of pure iodine is dissolved in 150 mL of alcohol.

2. Evidence for the dissolving of iodine can be obtained from all of the following **except** the
- A. change in conductivity of the solution
- B change in colour of the solution
- C. change in density of the solution
- D. heat transferred during the dissolving process

3. NR The amount concentration of the iodine solution is _____ mmol/L.

---

4. NR A sample of lake water contains 405 mg of dissolved minerals in 2.50 L of lake water. The concentration of dissolved minerals in parts per million is _____ ppm.

5. Dilution of stock solutions is an essential laboratory skill. If a lab technician needs to prepare 2.00 L of 2.50 mol/L ammonia solution, what volume of 14.8 mol/L concentrated ammonia will he require?
- A. 11.8 mL
- B. 33.8 mL
- C. 169 mL
- D. 338 mL

6. In the salt tank of a water softening system, excess sodium chloride forms a layer of solid below the salt solution. According to equilibrium theory, the explanation for the constant properties of the salt solution is that
- A. the concentration of the salt solution has become constant
- B. the rate of dissolving has become equal to the rate of crystallizing
- C. sodium chloride can no longer dissociate because the solution is saturated
- D. all of the water has been used up in dissolving the salt already present in the solution

Use this information to answer questions 7 and 8.

In a chemical analysis, a solution was found to have a hydronium ion concentration of 2×10^{-11} mol/L.

7. NR When this concentration is converted to a pH, the pH of the solution is _____.

8. Based on the pH, this solution may be classified as
- A. acidic
- B. basic
- C. neutral
- D. ionic

---

9. NR A cleaning solution with a pOH of 12.17 has a hydroxide ion concentration of $a.b \times 10^{-cd}$ mol/L. The values of ***a, b, c,*** and ***d*** are ___ ___ ___ ___.

10. As part of a chemical analysis of a window cleaning solution, the following evidence was obtained by testing samples of the cleaning solution with different indicators.
- Phenol red turned red.
- Both phenolphthalein and thymolphthalein were colourless.
- Bromothymol blue was blue.

The most likely pH of the solution is
- A. 10.0
- B. 9.4
- C. 8.1
- D. 7.6

11. If a solution of a strong acid is diluted by a factor of 10, the pH of the solution
- A. increases by one pH unit
- B. decreases by one pH unit
- C. increases by a factor of 10
- D. decreases by a factor of 10

12. One goal of chemical technology is to
- A. test current scientific laws and theories
- B. produce new chemical theories
- C. explain the nature of solutions
- D. solve practical problems

13. According to the modified Arrhenius theory, acids
- A. ionize into hydrogen ions
- B. react with water to produce hydronium ions
- C. react with water to produce hydrogen ions
- D. cause water to dissociate into hydrogen ions

14. A solution of sodium methanoate, NaHCOO(aq), has a pH of 8.3. Based on the modified Arrhenius theory, the chemical equation that explains this evidence is

A. $HCOO^-(aq) \rightarrow H^+(aq) + CO_2(g)$

B. $HCOO^-(aq) \rightarrow OH^-(aq) + CO(g)$

C. $HCOO^-(aq) + H_2O(l) \rightarrow H_3O^+(aq) + COO^{2-}(aq)$

D. $HCOO^-(aq) + H_2O(l) \rightarrow OH^-(aq) + HCOOH(aq)$

15. NR The following evidence was collected in an experiment to identify solutions at the same concentration and temperature.

Table 1 Experimental Evidence

Solution	Conductivity	pH
1	low	2.9
2	low	11.1
3	none	7.0
4	high	13.0
5	high	1.0
6	high	7.0

Identify, in order, the number of the solution that likely represents a

- strong acid
- weak acid
- strong base
- weak base

— — — —

16. According to the modified Arrhenius theory, a neutralization is a reaction between

A. an acid and a carbonate

B. an acid and an active metal

C. hydrogen ions and hydroxide ions

D. hydronium ions and hydroxide ions

17. When a polyprotic acid such as boric acid, $H_3BO_3(aq)$, reacts with water, the completeness of each successive reaction step

A. increases

B. decreases

C. stays the same

D. has no particular pattern

Part 2

18. **Distinguish** between the following terms:

(a) homogeneous and heterogeneous mixtures

(b) solute and solvent

(c) electrolytes and nonelectrolytes

(d) endothermic and exothermic dissolving

19. **Define** each of the following substances empirically:

(a) acid

(b) base

(c) neutral ionic substance

(d) neutral molecular substance

20. **How** is a hydronium ion different from an aqueous hydrogen ion? **How** is it similar?

21. Provide some examples from home or from your chemistry lab experience that illustrate the need to dissolve substances before they can react.

22. One brand of bottled water contains 150 mg of calcium in a 2.00 L bottle. **Determine** the concentration of calcium in

(a) parts per million

(b) moles per litre

23. A bottle of household vinegar is labelled 5% V/V acetic acid. **Determine** the minimum volume of vinegar that contains 60 mL of acetic acid.

24. Convert the following:

(a) 0.35 mol of NaCl(aq) in 1.5 L of solution into an amount concentration

(b) 25 mL of 0.80 mol/L $Mg(NO_3)_2(aq)$ into a chemical amount

(c) 0.246 mol of $NH_3(aq)$ in a 2.40 mol/L solution into a volume of solution

(d) 25.00 g of $CuCl_2(s)$ in 1.20 L of solution into an amount concentration

(e) 50.0 mL of 0.228 mol/L $Na_2CO_3(aq)$ into a mass of $Na_2CO_3(s)$

25. If water is added to a 25.0 mL sample of 2.70 g/L NaOH(aq) until the volume becomes 4.00 L, **determine** the concentration of the final solution.

26. DE Cement floors, especially in workshops, are often protected with an epoxy coating. Before applying this coating, the cement floor needs to be cleaned thoroughly. One part of this procedure usually involves an acid etching of the cement using hydrochloric acid (**Figure 1**).

(a) **Determine** the volume of 11.6 mol/L hydrochloric acid required to prepare 45 L of 3.5 mol/L solution.

(b) The preparation of this solution is potentially dangerous. **Plan** a procedure, including appropriate safety instructions, for preparing this solution.

Figure 1
Hydrochloric acid is sold as muriatic acid.

27. Write dissociation equations and calculate the amount concentration of the cations and anions in each of the following solutions:
(a) 2.24 mol/L $Na_2S(aq)$
(b) 0.44 mol/L $Fe(NO_3)_2(aq)$
(c) 0.175 mol/L $K_3PO_4(aq)$
(d) 8.75 g of cobalt(III) sulfate in 0.500 L of solution

28. **Compare** the ways in which concentrations of solutions are expressed in chemistry laboratories, consumer products, and environmental studies. Provide at least one example for each situation and include a possible reason for this choice.

29. In your own words, **describe** the rule relating the number of digits of a pH to the certainty (number of significant digits) of the hydronium ion concentration.

30. **Determine** the pH of each of the following solutions:
(a) lemon juice with $[H_3O^+(aq)] = 7.5 \times 10^{-3}$ mol/L
(b) $[HNO_3(aq)] = 2.5 \times 10^{-3}$ mol/L

31. **Determine** the hydronium ion concentration in each of the following solutions:
(a) cleaning solution with pH = 11.562
(b) fruit juice with pH = 3.5

32. **Sketch** a graph showing the relationship between pH and the hydronium ion concentration. **Describe** the relationship in a sentence.

33. State two main ways in which a theory or theoretical definition may be tested. Which method is the more stringent test?

34. **How** is the knowledge of pH useful in aquatic environments? **How** does this knowledge relate to both natural and manufactured products? Briefly **describe** two examples where knowledge of pH is used to solve practical problems.

35. DE A household cleaning solution has a pH of 12 and some fruit juice has a pH of 3.
(a) What is the hydronium ion concentration in each solution?
(b) **Compare** the concentration of hydronium ions in the fruit juice to the concentration of hydronium ions in the cleaning solution. How many times more concentrated is the hydronium ion in the juice than in the cleaning solution?

36. **Design** an experiment to determine which of six acids are strong acids and which are weak acids. Assume that you have solutions of known concentration available and all common laboratory equipment.

37. Hydrangeas (**Figure 2**) are garden shrubs that may produce blue, purple, or pink flowers. Research has indicated that their colour depends on the pH of the soil: blue at pH 5.0–5.5, purple at pH 5.5–6.0, and pink at pH 6.0–6.5. What colour of flower would be produced for each of the following soil acidities?
(a) $[H_3O^+(aq)] = 5 \times 10^{-7}$ mol/L
(b) $[H_3O^+(aq)] = 7.9 \times 10^{-6}$ mol/L

Figure 2
Hydrangea flowers

38. The term "weak" is sometimes used in non-scientific applications to mean dilute solutions. Why do we have to be careful not to use "weak" in this context when referring to acids and bases?

Use this information to answer questions 39 to 41.

Standard solutions of potassium hydrogen tartrate, $KHC_4H_4O_6(s)$, are used in chemical analysis to precisely determine the concentration of bases, such as sodium hydroxide. In one particular analysis, 100.0 mL of a 0.150 mol/L solution is required.

39. **Determine** the mass of potassium hydrogen tartrate that is required.

40. **Plan** a complete procedure for the preparation of the standard solution, including specific quantities and equipment.

41. Consult the MSDS for potassium hydrogen tartrate and sodium hydroxide and note precautions for handling these substances.

42. In a neutralization reaction of a strong acid and a strong base, how do the pH and pOH values change from their initial to their final values? **Justify** your answer by including a balanced chemical equation.

43. DE Laboratory safety rules require students to wear eye protection when handling acids, such as hydrochloric acid and sulfuric acid, yet dilute boric acid, $H_3BO_3(aq)$, is an ingredient in eye drops sold in drugstores (**Figure 3**). Although borates have been used for thousands of years in China, boric acid was not synthesized until 1702 in France. Soon after its synthesis, its mild antiseptic properties were discovered. **Explain** why some acids are more harmful than others. Your response should include

- at least two named examples of acids
- balanced chemical equations
- typical values of percent reaction with water

Figure 3
Boric acid is used in eye drops as a preservative and a buffer.

Use this information to answer questions 44 and 45.

Each of the following substances was dissolved in water to form a 0.1 mol/L solution, and then the pH of each solution was measured:

(a) $HCN(aq)$; pH = 5

(b) $HNO_3(aq)$; pH = 1

(c) $NaNO_2(aq)$; pH = 8

(d) $Sr(OH)_2(aq)$; pH = 13

44. Using the modified Arrhenius theory, write chemical equations to explain the pH evidence for each substance.

45. **Identify** the strong and weak acids and bases.

Use this information to answer questions 46 and 47.

Acids, such as nitric acid and nitrous acid, formed from the reaction of nitrogen oxides with water in the atmosphere, are components of acid deposition (such as acid rain).

nitric acid: $HNO_3(aq)$ nitrous acid: $HNO_2(aq)$

46. **Plan** an experiment to compare the acidity of nitric and DE nitrous acids. Your response should include

- an experimental design, with variables
- a list of materials required for the experiment
- a procedure indicating all steps, plus safety and disposal instructions

47. What are some negative effects of acid deposition? Provide several brief statements from a number of perspectives.

Use this information to answer questions 48 to 52.

Glycolic acid (hydroxyacetic acid, $CH_2OHCOOH(s)$) has many different uses, such as in household cleaning solutions (such as CLR®, **Figure 4**), and personal care products (such as skin creams). Aboriginal peoples used natural glycolic acids found in animal parts, such as brains, to tan hides. Glycolic acid is often used where a common strong acid would not be suitable for safety reasons. A 1.00 mol/L solution of glycolic acid has a pH of 1.92.

Figure 4
Glycolic acid is used in many household products, such as this bottle of cleaning solution.

48. Write the procedure and list the materials required to prepare glycolic acid solution and measure its pH as precisely as possible.

49. **Determine** the hydronium ion concentration of the solution.

50. Using the modified Arrhenius theory, write a chemical reaction equation to **explain** the acidity of glycolic acid.

51. If glycolic acid were a strong acid, what would its pH be? **Justify** your answer.

52. Suggest several other reasons why glycolic acid might be preferred in its many uses to a strong acid such as hydrochloric acid.

Use this information to answer questions 53 and 54.

Baking soda is one of the most versatile chemicals known. If you were to be stranded on an isolated island, baking soda would be one useful chemical to have available.

53. The acid–base properties of a baking soda solution are not easy to predict but can be explained using the modified Arrhenius theory. Knowing that a solution of baking soda turns litmus from red to blue, write chemical reaction equations, starting with solid baking soda, to explain the litmus evidence.

54. In a small group and using references, brainstorm a list of uses for baking soda. **Identify** any uses that involve acid–base reactions.

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55. What are some benefits and risks of using acidic and basic solutions in your home? Try to be specific about the risks by using WHMIS and Household Hazardous Product information. **Illustrate** your answer with some examples where you consider the benefits to exceed the risks, and other examples where you consider the risks to exceed the benefits.

56. DE Vinegar, a dilute solution of acetic acid, has a long history in human civilization. The word "vinegar" originates from a Latin word meaning "sour wine," which also indicates how it was made.

(a) Acetic acid is a common weak acid. Using the modified Arrhenius theory, write a chemical equation that explains the acidity of vinegar.

(b) If the pH of a sample of vinegar is 2.4, **predict** the hydronium ion concentration.

(c) If the sample of vinegar in (b) had a solute concentration of 1 mol/L, how does your answer to (b) show that acetic acid is a weak acid?

(d) Research the history of the uses of vinegar. **Enumerate** as many different uses as possible.

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57. The goal of technology is to provide solutions to practical problems. Most people associate technology with modern times, but technology, as practical products and processes, is as old as human civilization. Use the library or the Internet to research the modern-day precursor to Aspirin—the most widely used drug in the world—and how it was extracted and used by Aboriginal peoples in North America.

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58. Review the focusing questions on page 186. Using the knowledge you have gained from this unit, briefly **outline** a response to each of these questions.

Extension

59. Sulfuric acid, a strong acid commonly found in car batteries, is the largest-volume industrial chemical produced worldwide. Research and report, in pairs or small groups, on sulfuric acid production in industrialized countries. Your response should include

- why the volume of sulfuric acid consumed used as a measure of a country's degree of industrialization
- the names of some of the processes and products that involve sulfuric acid

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60. DE In the media, especially movies, acids are often portrayed as dangerous, with the ability to "burn through" or "eat away" almost anything. **Evaluate** this portrayal. Your response should include

- the accuracy of the typical media portrayal of acids
- justification of your evaluation with personal experience, examples, and explanations
- a list of the most dangerous acids, with reasons
- suggestions regarding how the media could more accurately portray the reactivity of acids

61. DE Many acids occur in nature. One common example is formic acid. Prepare a profile of formic acid. Your response should include

- natural occurrence in plants and animals
- general function in nature
- chemical formula
- safety and handling
- some technological applications

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62. The development of new pharmaceuticals usually involves acute toxicity tests on animals.

(a) **Define** acute toxicity. **Describe** the general testing procedure used.

(b) Animal testing is a controversial issue. **Identify** some positive and negative perspectives on this issue, including Aboriginal perspectives.

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